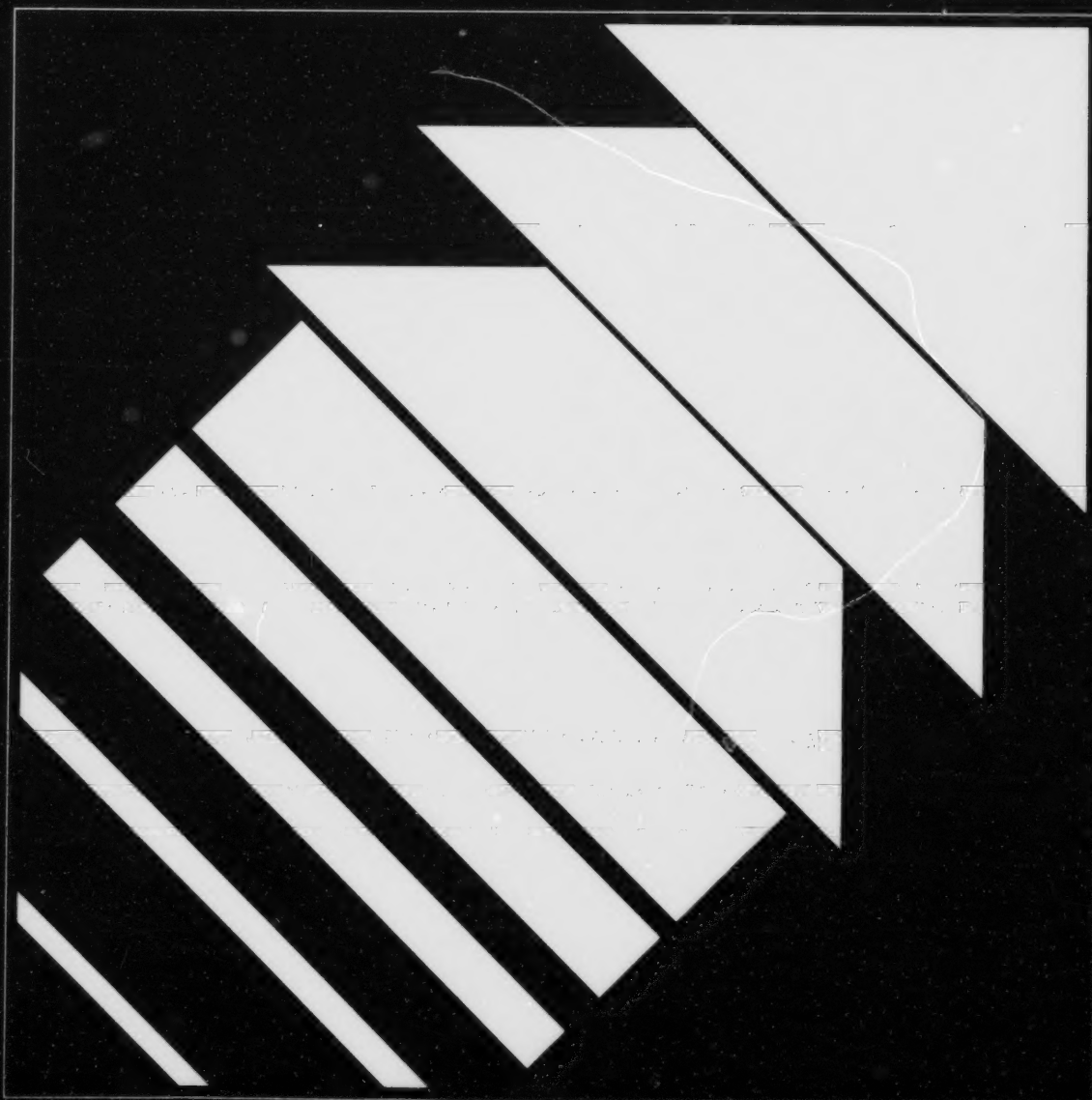
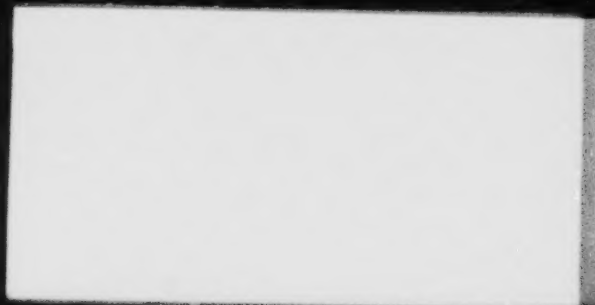


NATIONAL  
URANIUM  
TAILINGS  
PROGRAM



Energy, Mines and  
Technical Services Canada

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Canada

Literature Review for the National  
Uranium Tailings Program (NUTP) -  
Long-term Effects of Natural  
Events on Uranium Tailings  
Impoundments

NUTP 85-3 (TR)

A Research Report Prepared for:

The National Uranium Tailings Program  
Canada Centre for Mineral and Energy Technology  
Energy, Mines and Resources Canada  
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September 1985

175 pp

## S U M M A R Y

The purpose of this report is to determine the long-term effects of natural events on existing uranium tailings impoundments in Canada. The natural events studied were floods and heavy precipitation, high winds, earthquakes, forest fires and climatic change (glaciation, drought and the carbon dioxide-greenhouse effect). The investigated tailings sites were in northern Saskatchewan and at Bancroft and Elliot Lake, in Ontario.

Information about the natural events and the tailings sites was obtained from a literature search and from personal communications with experts in the respective fields. The analysis of the information was qualitative. It allowed conclusions to be made about the effects of every natural event studied at every Canadian tailings site. General conclusions included a ranking of the events in order of the severity of radionuclide release and a summary of the severity of future radionuclide release from each tailings site.

The overall conclusion was that all the tailings impoundments will probably fail severely in the very long-term, between 10 000 and 100 000 years from now.

It was recommended that the assessment of the effects of natural events be repeated when all the tailings sites are finally abandoned.

## S O M M A I R E

Le but du présent rapport est de déterminer les effets à long terme des événements naturels sur les bassins de confinement de résidus d'uranium canadiens existants. Les événements naturels étudiés furent les inondations et les précipitations abondantes, les vents violents, les tremblements de terre, les feux de forêt et les changements climatiques (glaciation, sécheresse ainsi que les effets serre des bioxydes de carbone). Les sites étudiés se trouvent au nord de la Saskatchewan ainsi qu'à Bancroft et Elliot Lake en Ontario.

L'information sur les événements naturels et sur les sites des résidus fut obtenue par une recherche de la littérature existante et des communications personnelles avec des experts dans les différentes matières. L'analyse de l'information était qualitative. Elle a permis de tirer des conclusions sur les effets de tous les événements naturels à l'étude à tous les sites de résidus au Canada. Les conclusions générales incluaient une classification des événements par ordre de rigueur des émissions de radionucléides et un sommaire de la rigueur future de ces émissions pour chaque site de résidus.

Les conclusions générales étaient que les bassins de confinement des résidus feront probablement défaut à très long terme, soit entre les prochains 10 000 à 100 000 ans.

Il fut recommandé que l'évaluation des effets des événements naturels soit reprise quand tous les sites de résidus seront abandonnés.



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## 1. INTRODUCTION

### 1.1 DESCRIPTION OF URANIUM TAILINGS

All ore mining and milling operations produce wastes, called tailings, that can vary in their environmental impact.

In the uranium milling process, rock containing uranium is ground to a fine size and then treated with chemicals to extract the uranium. The residual rock particles and process chemicals are tailings. These tailings undergo preliminary treatment and are transported as a water slurry to an impoundment basin.

Although uranium mill tailings make up only a small proportion of the total tailings produced in Canada, interest in their environmental effects is widespread because of their radioactive content. They also contain heavy metals and sometimes acid-generating materials. The principal radioactive components, or radionuclides, in uranium tailings are isotopes of uranium, radium, thorium, polonium and lead. If released in sufficient quantities into the environment, radionuclides can increase in concentration to where they become a hazard to the environment and to man (1).

### 1.2 URANIUM TAILINGS IN CANADA

Uranium mining and milling operations have been conducted in Ontario and northern Saskatchewan since the mid-1950's. By 1982 approximately 126 million tonnes of tailings had been produced. The total could double by the end of the century (2).

The bulk of the uranium mine tailings, 81 per cent (102 million tonnes), are located in the Elliot Lake area of Ontario. Approximately 14 per cent (18 million tonnes) are located in northern Saskatchewan and 5 per cent (6 million tonnes) in the Bancroft area of Ontario (2). The location of uranium tailings areas and some of the significant deposits are shown in Figure 1 (see also Appendix D).

Of the total quantity of tailings, approximately 34 per cent (43 million tonnes), are located in inactive or decommissioned tailings impoundments which no longer receive tailings. The majority of these tailings impoundments were operated from the mid-1950's to the mid-1960's and have been inactive since that time. The remaining 66 per cent (83 million tonnes) of tailings are located in active tailings impoundments which currently receive tailings (2).

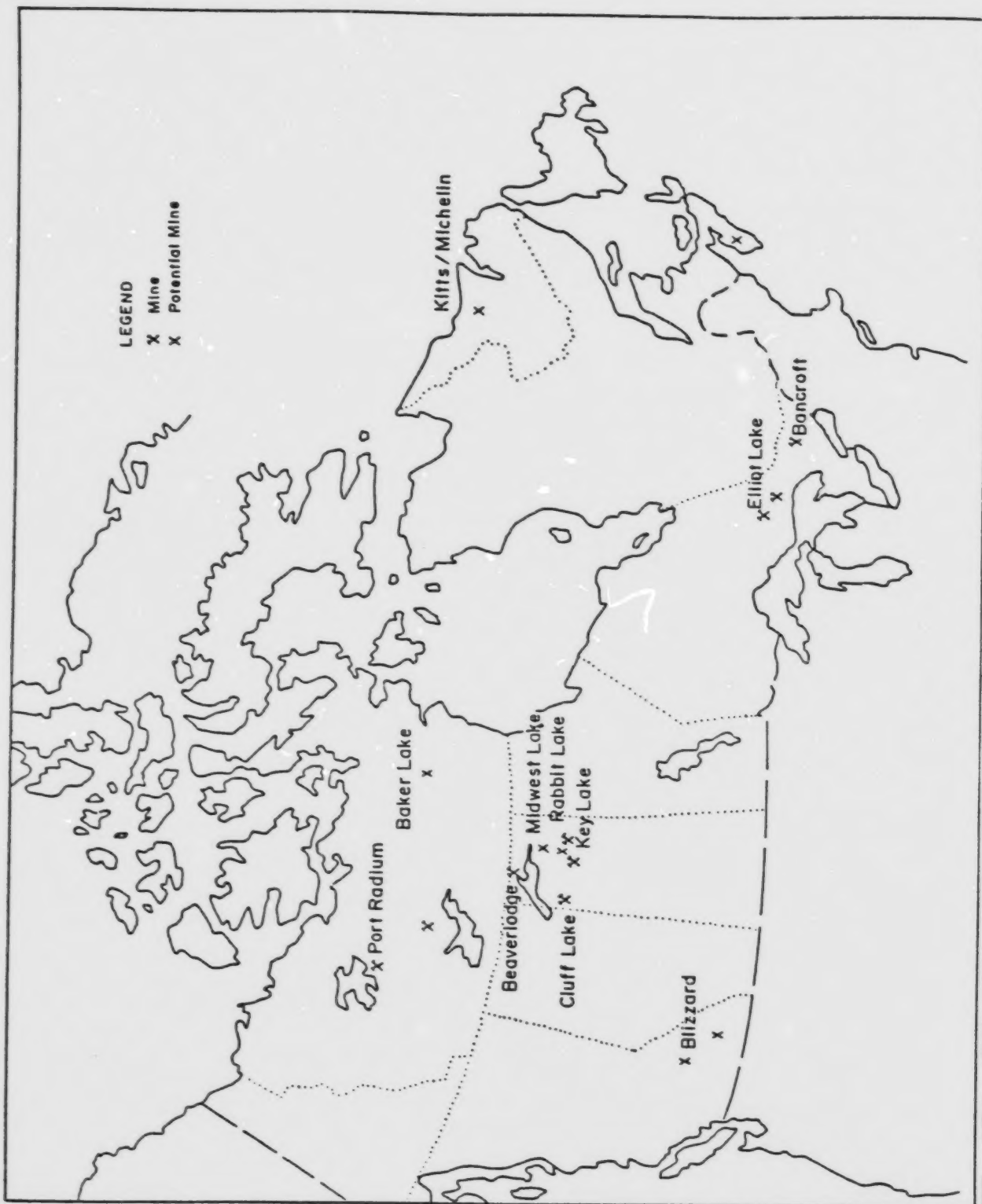


Figure 1. Uranium mining areas in Canada

### 1.3 NATIONAL URANIUM TAILINGS PROGRAM

In 1981, after a year-long study, the National Technical Planning Group on Uranium Tailings Research concluded that there was not enough scientific data to predict confidently the long-term effects of uranium tailings on mankind and the environment. This group of experts, appointed by the Department of Energy, Mines and Resources Canada, recommended that a research program be conducted to fill the knowledge gap.

Thus, in 1982, the Government of Canada announced the National Uranium Tailings Program (NUTP), a five-year research program to focus on predicting the effects on the environment of uranium mine tailings and the effluent from them over the long-term (3).

The NUTP is part of the Minerals and Earth Sciences Program of Energy, Mines and Resources Canada. It forms part of the Mineral Sciences Laboratories of the Canada Centre for Mineral and Energy Technology (CANMET).

The main objective of the Program is to provide a scientifically credible information base that will assist government regulatory agencies in making confident, knowledgeable decisions, and in establishing criteria for the long-term protection of the environment and human health. The scientific information base will, among other things, describe the chemical and physical processes that involve tailings constituents and their movement along pathways from the tailings into the biosphere (1).

There is little information about the interaction of uranium tailings with the environment, particularly over long periods. This report examines the effects in the long-term, of natural events on Canadian uranium tailings impoundments. Sections 2 to 6 deal with precipitation and floods, high winds, earthquakes, forest fire and climatic change respectively. Site specific analyses and conclusions are made where possible.

The longevity of tailings impoundments is discussed in Section 7, Section 8 contains general conclusions and in Section 9 a recommendation is given.

## 2. HEAVY PRECIPITATION AND FLOODING

### 2.1 GENERAL CAUSES OF FLOODING

Flooding can result from large rainstorms, rapidly melting snow, localized cloudburst storms, and river ice-jamming. Sometimes snowmelt runoff may be augmented by rain, leading to very high peak flows and severe flooding.

### 2.2 EFFECT ON TAILINGS IMPOUNDMENTS

The failure mechanism associated with floods for tailings impoundments is erosion. Floods can damage tailings structures by erosion of the toe of an embankment or by overtopping. Any erosion of tailings during flooding will result in the transport of solids for great distances. Tailings impoundments built across natural drainages are usually more susceptible to flood damage than those that are not (4).

Floods can interact with many of the other elemental failure mechanisms of a tailings impoundment, especially those which cause erosion or affect slope stability. Small floods from high intensity rainfall can cause gulying, sheet erosion, increased sediment transport into diversion structures, and damage to vegetation on reclaimed surfaces. Large floods can result in embankment instability due to erosion of the toe, overtopping and washout of diversion facilities, or overtopping and washout of tailings embankments (4).

Increases in soil moisture which may be associated with a flood may also contribute to slope instability. Landslides often occur in natural slopes following periods of heavy rainfall (4).

Some tailings impoundments may be left as reservoirs after they have been closed-out. A tailings impoundment that acts, in part, as a reservoir is strongly influenced by the water level. A high water level can be attained in a short time by a severe rainstorm, or over a long time (weeks or months) by an extended above-average runoff. Perimeter embankments must provide sufficient freeboard for storage of runoff from both types of events. Furthermore, to avoid failure of the perimeter embankments, an emergency spillway should be provided. Overtopping of a perimeter embankment not specifically designed for overtopping would probably cause it to fail. The failure would probably be very serious because it would result in the loss of contaminated water and tailings slimes from the impoundment (5).

In general, the dominant erosive agent in most areas, including many arid regions, is flowing water (6).

### 2.3 FLOOD PROBABILITIES

### 2.3.1 General Case

In any particular year, the average probability of occurrence of any flood greater than the 100-year return period flood is 0.005, which is equal to the probability of the 200-year return period flood. In general, the average probability of all floods greater than the X-year return period flood is  $1/(2X)$ , which is equal to the probability of the 2X-year return period flood (7, 8).

### 2.3.2 Structures and their Design Floods

There is a 63 per cent chance that a structure designed for the 100-year return period flood will have its capacity exceeded in 100 years. At a 95 per cent confidence level that the capacity of a structure will not be exceeded in 100 years, it must be designed for the 1950-year return period flood (9). These two probabilities show how significantly the return period of a structure's design flood must increase if the structure is to be reasonably safe for as short a time as one century. Table 1 lists more probabilities of X-year floods occurring within selected time intervals.

| Event Return Period (years) | Time Interval (years) |     |     |      |        |        |
|-----------------------------|-----------------------|-----|-----|------|--------|--------|
|                             | 1                     | 10  | 100 | 1000 | 5000   | 10000  |
| 500                         | 0.2                   | 2   | 18  | 86.5 | 99.995 | 99.999 |
| 1000                        | 0.1                   | 1   | 9.5 | 63   | 99.33  | 99.99  |
| 5000                        | 0.02                  | 0.2 | 2   | 18   | 63     | 86.5   |

TABLE 1. Per cent probability of occurrence of extreme events within selected time intervals (10).

### 2.3.3 Relationship Between Precipitation and Flooding

It can be assumed that a rainstorm of a given recurrence interval produces a runoff event of the same recurrence interval. For example, a 25-year return period rainstorm may cause a flood of considerably lower or higher recurrence interval. On the average, however, it will produce a 25-year return period flood (11).



There is a maximum flood of which a given catchment basin is capable. It is determined by the rainfall and the characteristics of the catchment basin (12).

The previous two points are related by the concept of probable maximum precipitation (PMP) and probable maximum flood (PMF). The PMP of a location is an estimate of the maximum rainfall event that can ever occur at that location. The PMF of a location is an estimate of the largest flood event that can ever occur at that location. The PMF is expected to result from the PMP.

## 2.4 ANALYSIS OF THE ONTARIO SITES

Annual maximum floods in Ontario result from either snowmelt, snowmelt and rain, or rain falling on saturated ground (13). Watersheds in southern Ontario have two distinct types of flooding: those due to precipitation only, generally occurring in the summer, and those due to snowmelt (sometimes combined with precipitation), generally occurring in the winter or spring. Several studies support the idea of two types of flooding in southern Ontario (14).

The Elliot Lake and Bancroft areas are in the Canadian Shield. The humid climate and swampy basins of the Shield formation prevent a substantial variation in the flow of rivers from occurring (15).

None of the tailings sites is located in the flood plain of a river that floods by ice-jamming. Hence, ice-jamming is one general cause of flooding which is not considered important.

Two types of storms produce the greatest rainfalls in southern Ontario: tropical cyclones and thunderstorms (9). The precipitation effects of tropical cyclones are more significant than their wind effects. The ratio of runoff to precipitation is greater for tropical cyclones than for summer thunderstorms. This is because the ground is wetter in the autumn -- when tropical cyclones occur -- than in the summer (9). Wetter ground results in less infiltration.

The hydrologic criteria involving acceptable risks of failure for tailings impoundments in Ontario have not been clearly defined by the regulatory agencies. Existing guidelines do not stipulate a hydrologic criterion for the design of an emergency spillway specifically for this type of impoundment (5). However, tailings embankments are now commonly designed with a freeboard allowance and control structure capacity to handle either a 100-year return period storm or regional storm (16).

### 2.4.1 Bancroft

#### 2.4.1.1 General

The tailings in the Bancroft area are near the headwater regions of the Eels Creek and Crow River drainage systems. There is no history of flooding in these headwaters. Bow Lake, for example, has no potential for flooding. Bow, Bentley, Centre, Auger and Farrel Lakes are small headwater lakes with good drainage. In Bentley, Deer and Farrel Creeks, spring melt flows do not seem to pose a problem (17).

The maximum recorded rainfalls in the Bancroft area are 25 mm in 15 minutes and 83 mm in one day (18). These amounts could cause serious flood problems in the long-term at the tailings sites.

#### 2.4.1.2 Madawaska

Direct precipitation is the only source of water now entering the Madawaska tailings impoundments (19). However, there is a potentially erosive creek (Bentley) that runs along the base of the waste rock tailings retention dam of Madawaska Impoundment No. 2. It follows the perimeter and in the long-term the creek may erode the toe of the embankment causing the release of a significant amount of tailings. The magnitude of release cannot be estimated.

#### 2.4.1.3 Bicroft

The Auger Lake tailings are in the lake, on the shoreline and form beaches around the lake. They probably will not be transported from the lake because the lake does not flood and water flowing through it is slow. However, failure of the decant structure on the lake could cause a failure of the south tailings embankment resulting in discharge of tailings into Deer Creek and thence into Paudash Lake (20). The decant structure will inevitably fail because all such structures requiring maintenance usually fail in the long-term. Therefore, tailings release at Auger Lake due to flood-caused failure of the south tailings embankment, is a large threat.

The range of Paudash Lake's water level fluctuations is a little over one metre (19). This range is not enough to bring the lake into contact with the Bicroft tailings and therefore, Paudash Lake poses no flooding threat to the tailings.

The tailings in the Bicroft swamp are flooded because of beaver activity (21). The flooding may or may not release a significant amount of radionuclides from the swamp.

#### 2.4.1.4 Summary

Floods of several different causes may release a significant amount of radionuclides from the Bancroft tailings sites. The probable causes include the failure of the decant structure at Auger Lake; heavy precipitation and/or snowmelt runoff resulting in high water levels in Bentley Creek; and beaver activity in the Bicroft swamp.

## 2.4.2 Elliot Lake

### 2.4.2.1 Serpent River Basin

The Elliot Lake tailings areas lie in the Serpent River basin. The basin has an area of about 1375 km<sup>2</sup> (21-23). It has a uniform climate and physiography and is characteristic of watersheds in the Canadian Shield in that it experiences climatic extremes (i.e., cold winters and warm summers); a generally humid climate with uniform annual precipitation; a thin soil cover on almost non-weathered rock; numerous lakes, ponds and swamps; and extensive forests (21-23). The lakes, ponds and swamps moderate wide fluctuations in river flows resulting from short-term rainfalls and spring snowmelt (23). For example, many streams in the basin are extremely variable in flow, but the extensive storage provided by the lakes exercises a moderating effect on the flows in the Serpent River (22). The runoff coefficient (ratio of runoff amount to precipitation amount) for the basin is 0.7 (Appendix C).

There are two high-flow peaks per year. The largest peak is associated with spring runoff, and a lesser one occurs in the late autumn when persistent rainfalls occur on the ground which may be partially frozen (21).

### 2.4.2.2 Design Rainstorms

The regional flood of a location is defined as the largest known rainfall event to have occurred at that location. For northern Ontario basins, the regional flood is the Timmins Storm. It is often used as the design event for structures influenced by heavy precipitation and floods. The Timmins Storm was centered over the Timmins area from August 30 to September 1, 1961 and produced the greatest amount of rainfall on record in the area. At the center of the storm, it produced 19 cm of rain in a 12-hour period (24). The probable maximum precipitation (PMP) in the Elliot Lake area is 42 cm in 12 hours (23, 25). Other design storm events used with their total precipitation are:

- 10-year: 7 cm
- 25-year: 9 cm
- 100-year: 16 cm

Duration of all the above events is 12 hours (25). The 100-year storm has been used most often, therefore, many impoundment failures caused by rainstorm runoff should occur within one to two thousand years.

### 2.4.2.3 Flood Threats to Tailings

None of the tailings sites is located in a regional flood plain. Most of them are at the top of their local watershed and, therefore, cannot be influenced by flooded rivers and lakes. The tailings containment basins cover not less than one-third the area of the watersheds that drain into them (26). In most cases, the flood threat is from direct precipitation only (27). The runoff coefficient is quite high (0.7) resulting in significant direct precipitation effects.

Impoundment structures built in the last ten years can discharge the probable maximum flood (PMF) without being destroyed (28). The Denison tailings sites -- Stanrock, Long Lake and William's Lake -- are said to be able to prevent radionuclide release during the 200-year flood (27).

The flooding threats at the Quirke tailings site can be used as examples of what may happen at the Elliot Lake sites in general. Over the long-term, a wet season consisting of a series of minor precipitation and/or snowmelt events may be more critical in the design of a storage reservoir than a brief, intense major storm. Large fluctuations in the reservoir water level elevation can occur in response to wet and dry seasons when the reservoir is small in relation to its watershed. This is similar to the situation found at the Quirke tailings site (22). A more specific threat is the possibility of failure of Dam E at the lower end of the settling pond. If failure were caused by a flash flood or by a particularly heavy spring runoff, much of the contained barium-radium sulphate sludge could be flushed into the Serpent River watershed resulting in a major radionuclide release (25).

#### 2.4.2.4 Flooding Incidents

There have been a number of flood-related problems at the tailings sites.

During the Timmins Storm, the settling pond culvert downstream from the Long Lake tailings site was blocked with debris. Backed-up water breached the pond dyke causing an uncontrolled release of the pond water (27).

At the Panel tailings site, beavers have dammed weirs and channels. The problems caused by this have been prevented only by monthly maintenance. Beaver damming in conjunction with a 10- or 25-year rainstorm would cause overtopping of the tailings embankments (28).

In the spring of 1983, a broad-crested dam on the Quirke site was washed out. It was at the last control point of effluent treatment downstream from the tailings. The dam itself was the water outlet structure and the water flowed over it. Ice jammed against the dam, channelling the water flow into a narrow width. The erosion caused by the channelling quickly breached the dam and the breach reached a depth of three metres. Some tailings slimes flowed downstream as a result.

In 1968, a piping failure of an unengineered wasterock embankment occurred at Stanleigh. Also, a decant tower freeze-up once caused overtopping of a tailings embankment at that site (28).

In the spring of 1985, a decant tower on the Nordic Main was plugged by debris. Water levels rose rapidly and if pumping had not been initiated, overtopping would have occurred because the impoundment was not designed to handle excess water. This incident occurred during a normal spring runoff. If a flood event of as little a return period as ten years had occurred at the same time, a major overtopping problem would have resulted (28).

A Stanrock site embankment, originally constructed using tailings, allowed tailings spills some years ago, due to both decant tower failure and overtopping. The decant tower failure occurred in June, 1964. It released 450 000 tonnes of tailings into Moose Lake, and thence into Orient Creek (29).

The occurrence in the last twenty years of this number and variety of flood-related radionuclide releases means that in only several hundred years, radionuclide release from flooding will probably be great. Total release could occur at some sites in the long-term.

#### 2.4.2.5 Summary

Flooding at the tailings sites will probably be caused by rainstorms. They could be either intense summer thunderstorms of short duration or tropical cyclones of long duration. Rainstorm runoff may cause many severe impoundment failures within one to two thousand years, though there could be a great amount of radionuclide release within only several hundred years. Failures may occur through all flood-related failure mechanisms including piping of embankments, embankment overtopping and washout, and embankment instability due to erosion of embankment toes. At some sites, the failures will probably allow major radionuclide release.

### 2.5 ANALYSIS OF SASKATCHEWAN SITES

As in Ontario, all the tailings sites are in the Canadian Shield. The watersheds containing the sites also contain many typical Shield lakes which produce relatively stable discharge with little seasonal change (30). The runoff coefficient in this region is 0.9 and is considered very high (Appendix C).

#### 2.5.1 Lorado

Nero Lake probably has no significant effect on the tailings which border it. However, the tailings are fully exposed to the precipitation runoff from the local watershed and are heavily eroded by it. The maximum recorded rainfalls at Uranium City are 8 mm in 15 minutes and 47 mm in one day (18). These amounts are relatively light, but can have significant effects on fully exposed tailings. Gullying and sheet erosion have already released a large amount of radionuclides to the environment, and will probably always do so.

#### 2.5.2 Gunnar

About one-third of the Gunnar tailings suffer the same water erosion as the Lorado tailings. The maximum recorded rainfalls at Uranium City apply here also.



The Langley Bay tailings can be heavily eroded by the bay, though it is not known whether or not they are. The following shows the potential of Lake Athabaska to wash away the Langley Bay tailings through changes in its water level. The probability that the lake level will equal or exceed one metre below or above the mean level in any one year due to natural causes is ten per cent. However, during at least one day of each year, there is a 25 per cent chance that the water level will be more than one metre below or one metre above the mean. For one year in every five years the level will exceed one metre above or below the mean lake elevation. The probability that the lake level will change by more than three metres in any one year is approximately two per cent (31). Lake level data from Crackingstone Point, near Langley Bay, show that the lake level changes by more than one metre every year. During many years, the range of fluctuations in lake level exceeds even two metres (32).

The potential for flooding by local creeks is not known. But gullying and sheet erosion of the exposed tailings and lake water erosion of the Langley Bay tailings may eventually release large amounts of radionuclides to the environment.

#### 2.5.3 Beaverlodge

Most of the tailings are in Fookes and Marie Lakes. The tailings actually benefit from water cover. Water cover is a proposed closeout method that has been shown to work well for tailings (33). The range of water level fluctuations in these lakes is 1.5 m (33). Hence, the lakes will flood the tailings, but will probably not disturb them significantly.

Under extreme conditions of the 100-year lake flow, velocities generated would be sufficient to disturb the material in near-shore areas. However, because of the very low velocity of flow through these lakes even under such severe conditions, it is expected that the disturbed material would be redeposited in deeper water before leaving the lakes (34).

The evidence shows that significant release of radionuclides to the environment will probably never occur.

#### 2.5.4 Rabbit Lake

The Rabbit Lake impoundment is at the divide of two local drainage basins, one draining to the north, and the other, to the south, both into Wollaston Lake. The catchment basin which contributes water to the tailings impoundment is slightly bigger than the impoundment itself. There is not much extra runoff contribution from any other area. Also, it is practically impossible for flood waters from nearby lakes and rivers to reach the base of the impoundment (35).



The maximum recorded rainfalls at Rabbit Lake are 9 mm in 15 minutes and 73 mm in one day (18). These amounts would not cause a flooding problem because of the impoundment's high position in the local drainage basins, and the small size of the catchment basin in which the impoundment lies. Therefore, if heavy precipitation and flooding ever cause impoundment failure, it will probably be through gullying and sheet erosion. Release of radionuclides from the impoundment by this water action will probably not occur for at least one hundred years. Release will always be limited, sometimes even prevented by vegetation cover (see Section 5.6).

#### 2.5.5 Key Lake

The existing closeout concept for Key Lake employs a natural top-seal which will be graded to rapidly shed all precipitation away from the tailings impoundment. This is designed to exclude almost all radionuclide release to groundwaters and surface waters from occurring (36).

The following rainfall amounts and corresponding durations were used for design purposes at Key Lake (37):

- 100-year rainfall, 24 hours: 7.5 cm
- 100-year rainfall, 10 days: 21.5 cm
- probable maximum 10-day precipitation: 75 cm

No stream enters any part of the site. Therefore, there is no possibility of flooding from streams at their peak flows (38). Also, the impoundment is located out of reach of the maximum water levels of the surrounding lakes. The water levels do not even fluctuate by more than one metre (39). Therefore, there is no flooding danger from lakes.

The impoundment is on a ridge which is a local topographic high. Surface water does not exist on the ridge itself and temporary ponding of water has never been detected there. As observed in other parts of the Key Lake area, the infiltration capacity on the ridge is so high that even during heavy rainfalls no ponding of surface runoff occurs (40).

It is not known what the design rainstorm of the impoundment is. However, because of the impoundment's ideal location relative to the local lakes and streams and of the characteristics of the ridge on which it is situated, heavy precipitation effects should be the same as at Rabbit Lake. It will be at least one hundred years before heavy precipitation can cause impoundment damage. Gullying and sheet erosion will probably be the failure mechanisms, but at Key Lake, as at Rabbit Lake, they will be limited, sometimes prevented, by vegetation cover (see Section 5.6).

## 2.6 CONCLUSIONS

- Floods caused by heavy precipitation and/or snowmelt runoff, beaver activity and decant structure failure may release a significant amount of radionuclides from the Bancroft sites.
- Flooding of the Elliot Lake tailings sites will probably be caused by either summer thunderstorms or tropical cyclones. Rainstorm runoff may cause many severe impoundment failures within one to two thousand years, though there will probably be a great amount of radionuclide release within only several hundred years. Failures could occur through all flood-related failure mechanisms. At some sites, major radionuclide release will ensue.
- At Lorado, gullying and sheet erosion have already released a large amount of radionuclides to the environment and will probably always do so.
- At Gunnar, large amounts of radionuclides will probably be released to the environment by gullying and sheet erosion of the exposed tailings and by lake-water erosion of the Langley Bay tailings.
- At the Beaverlodge site, significant release of radionuclides, because of flooding, will probably never occur.
- At the Key Lake and Rabbit Lake sites, release of radionuclides will probably not occur before one hundred years from now. If it occurs, it will probably be through the mechanisms of gullying and sheet erosion. Vegetation cover on the impoundments, however, will limit or sometimes prevent, these failure mechanisms from occurring.

### 3. HIGH WINDS

Wind erosion is such a constant process that it could remove a tailings impoundment within 100 000 years (Appendix A). It threatens to disperse radionuclides through tailings suspension, saltation and creep. At some Canadian and American sites, tailings fines have been wind-blown for hundreds of metres. According to Shepherd, the effect of wind-blown tailings is probably not dangerous (41). The following paragraph explains his view.

" Mill tailings are prone to wind erosion. The effects of wind erosion fall into two groups: those which destabilize impoundments and those which do not. Normal winds can eventually blow a large amount of tailings from an impoundment without destabilizing it. In fact it is probable that stability will not be lessened. But high winds can form blowouts in embankments, weakening them. Blowouts are the most severe wind effect (41)."

Shepherd raises two more points. The first is that wind will not erode an impoundment with a rip-rap or vegetation cover (the vegetation cover need not be 100 per cent). Secondly, wind-eroded embankments made of coarse material will eventually self-armour; this armouring process is the same as that which forms desert pavements in arid regions.

The following three sections describe the sources of high winds.

#### 3.1 TORNADOES

Tornadoes do not occur in northern Saskatchewan. Bancroft and Elliot Lake lie in a zone of average annual tornado frequency of 0.4 - 0.8/10 000 km<sup>2</sup>. Most of the tornadoes are in the F0 to F2 range of the F-Scale (Appendix B). The average annual tornado frequency of F2 to F5 is 0.05 - 0.1/10 000 km<sup>2</sup> (42).

A severe, damaging storm, known as "The Sudbury Tornado" occurred the morning of August 20, 1970. It traced out a path starting from 30 km west of Elliot Lake, Ontario through the Whiskey-Savage Lake areas, through the regional municipality of Sudbury, and onward to the north of Temiscaming, Quebec. The tornado levelled the forest where it touched down on the shore of Whiskey Lake (43).

The above information shows that the Elliot Lake and Bancroft impoundments may be struck by several tornadoes in the next few hundred years. The tornadoes will blow a small amount of tailings from bare impoundments, over a wide area. Shepherd (Appendix A) concludes that the effect of tornadoes is forever insignificant. Though they are the most destructive of all winds, their duration at a site is too short to weaken an impoundment (44).

### 3.2 TROPICAL CYCLONES

Tropical cyclones have intensity stages (45):

Tropical storm - A tropical cyclone with highest sustained wind speeds of 62-118 km/h.

Hurricane - A tropical cyclone with highest sustained wind speeds of 119 km/h or more.

Extratropical storm - A tropical cyclone modified by interaction with non-tropical air masses, and extratropical weather systems. Winds may remain above hurricane force in some cases.

There is extremely little chance that a tropical cyclone will ever travel to northern Saskatchewan because there is no record of one occurring in Canada west of Sault Ste. Marie (46). Therefore, the Saskatchewan impoundments will never be affected by tropical cyclones.

In the period 1871-1899, seven tropical cyclones passed between Sault Ste. Marie and Bancroft; four were hurricanes (47).

Out of some 358 Atlantic tropical cyclones during the fifty year period, 1900 to 1949, only 25 had any noticeable effect on the weather of southern Ontario and only eight of these caused high winds and/or excessive rain in the province (48).

In the period 1950-1963, three extratropical storms passed between Sault Ste. Marie and Bancroft (47).

The hurricane return period at Elliot Lake is 100-200 years. It is 30 years at Bancroft (46).

When tropical cyclones reach Ontario, their winds are rarely, if ever, of hurricane speed ( $\geq 119$  km/h). However, they may be very strong; the highest sustained wind speed recorded in Ontario during hurricane Hazel (October, 1954), was 90 km/h (49). Winds of tropical cyclones in Ontario, are not stronger than severe thunderstorm winds. Their infrequent occurrence limits their effect on tailings. Radionuclide release by tropical cyclones is therefore likely to be small.

### 3.3 LOW PRESSURE SYSTEMS IN GENERAL

At the Saskatchewan and Ontario sites, damage to tailings impoundments from high winds is normally due to the low pressure storm systems that are a regular part of the weather. In comparison, tropical cyclones pose a small threat.

Low pressure storm systems travel through the tailings sites many times during a year. Hence, every year, some will have higher winds than normal. This may cause the formation of blowouts. Low pressure system winds occur all year, though they are most intense in the winter because of the great contrast in temperature between northern and southern air masses. They are least intense in the summer (50). Winter high winds generally occur after the passage of a cold front and may last from a few hours to several days (50).

Thunderstorms are a common summer source of high winds. They develop suddenly and are characterized by violent irregular gusts (44). Peak gusts from thunderstorms in Saskatchewan and Ontario lie between 70 and 90 km/h (19.2 and 25 m/s) (46). These statistics were derived from data recorded at weather stations near the tailings sites. The longest period of record of the data was 1955-80; the shortest, 1961-80.

### 3.4 SITE ANALYSIS

Factors affecting wind erosion of tailings impoundments are: moisture content, particle size distribution, cover extent and wind speed. Moisture decreases the rate of wind erosion.

The amount of dust moved varies approximately with the cube of the wind speed (15). Wind speed is very dependent on site topography (51). Table 2 lists the winds of recurrence intervals of 10, 30 and 100 years at the tailings sites. The Beaufort Scale (Appendix B) classifies wind according to its speed; the scale is an aid for understanding the significance of the data in Table 2.

| Location     | Peak Hourly Winds (km/h, m/s) |           |           |
|--------------|-------------------------------|-----------|-----------|
|              | 10 years                      | 30 years  | 100 years |
| Bancroft     | 68, 18.9                      | 76, 21.1  | 85, 23.6  |
| Elliot Lake  | 75, 20.8                      | 84, 23.3  | 94, 26.1  |
| Gunnar       | 83, 23.1                      | 92, 25.6  | 101, 28.1 |
| Key Lake     | 93, 25.8                      | 101, 28.1 | 111, 30.8 |
| Rabbit Lake  | 88, 24.4                      | 103, 28.6 | 119, 33.1 |
| Uranium City | 86, 23.9                      | 95, 26.4  | 103, 28.6 |

TABLE 2. Peak hourly winds of selected recurrence intervals at the tailings sites (52).



Figure 2 shows the rate of movement of an average dune sand against wind speed (53). Although tailings are not an average dune sand, the curve is similar to the relationship between tailings and wind speed. This is because the quartz content of uranium ores is in excess of 65 per cent (54). Silica particles are less prone to suspension in air than other tailings particles (54). Therefore, the rate of movement is adjusted to a higher amount when applying Figure 2 to tailings materials.

Figure 3 plots particle size against the lowest (threshold) wind speed required to move a particle. The curve is called the fluid threshold. The fluid threshold is the wind speed at which the direct pressure of the wind alone, starts particle movement (53).

#### 3.4.1 Bancroft

The Bancroft tailings will probably support full forest cover within one hundred years (see Section 5.3.1). After this time, no wind erosion will occur.

In the meantime, wind may damage Madawaska Impoundment No. 1 because it is only partly covered with rip-rap.

The other tailings (Dyno, Bicroft and Madawaska No. 2) lie in low areas and they are not very exposed. A large amount of natural vegetation grows on them already. Some of the Bicroft tailings are water-covered and hence, will not be wind eroded. Table 2 shows that Bancroft's storm winds are by far, the lowest of all the tailings sites. These four factors show that wind erosion of the tailings will probably not be significant.

#### 3.4.2 Elliot Lake

Wind erosion may occur for several decades after closeout; a substantial vegetation cover will establish itself in that time (see Section 5.3.2).

The majority of surface tailings are dry. The hot summer will quickly dry tailings, thereby increasing dust formation. Air transport of tailings at Elliot Lake is consequently most severe during the summer (16). Dust blow of tailings is reduced by snow, frost or rain approximately 45 per cent of the year (15).

The surface tailings size distribution, given in Table 3, at Stanrock represents the Elliot Lake sites well.



| Grain diameter<br>mm | Percentage of surface tailings<br>% |
|----------------------|-------------------------------------|
| 0.3 - 0.1            | 40                                  |
| 0.1 - 0.04           | 23                                  |
| 0.04 - 0.01          | 17                                  |
| 0.01 - <0.1          | 20                                  |

TABLE 3. Surface tailings size distribution at Stanrock (54).

Comparison with Figure 3 reveals that this size distribution is very susceptible to wind transport. Ninety-four per cent of the tailings are transportable by air (16).

Winds in Elliot Lake do not attain very high speeds (Table 2). The tailings are sheltered because they are in lake basins (Appendix C).

The above factors are inconclusive. However, surface tailings wind erosion has always been a problem (55).

The Elliot Lake model impoundment (Appendix C) has a coarse till shell in its dykes. The embankments will probably self-armour before their stability is weakened by erosion from high winds. Therefore, embankment erosion poses little problem.

The evidence shows that high winds pose more of a problem in Elliot Lake than in Bancroft and significant tailings release may occur in the next several decades. Embankment blowouts, however, should not occur.

### 3.4.3 Saskatchewan

#### 3.4.3.1 Lorado

High winds may eventually transport a large portion of the tailings. Their surface moisture content is low (56). They have no cover and are unstable. Their exposure too, ensures their erosion; the tailings are little sheltered by the land. Much of the tailings could be transported within a few hundred years.

#### 3.4.3.2 Gunnar

Probably at least one-third of the tailings will always be bare (see Section 5.3.3.2). They are windblown and cover the tree trunks at the tailings pond edge up to one metre in depth. All the tailings are exposed and have a loose texture and a low moisture content (56). A comparison of Figure 2 and Table 2 shows that Gunnar's high winds move a lot of tailings. A freeze-thaw effect, increasing the wind erosion rate, is thought to occur here (57).

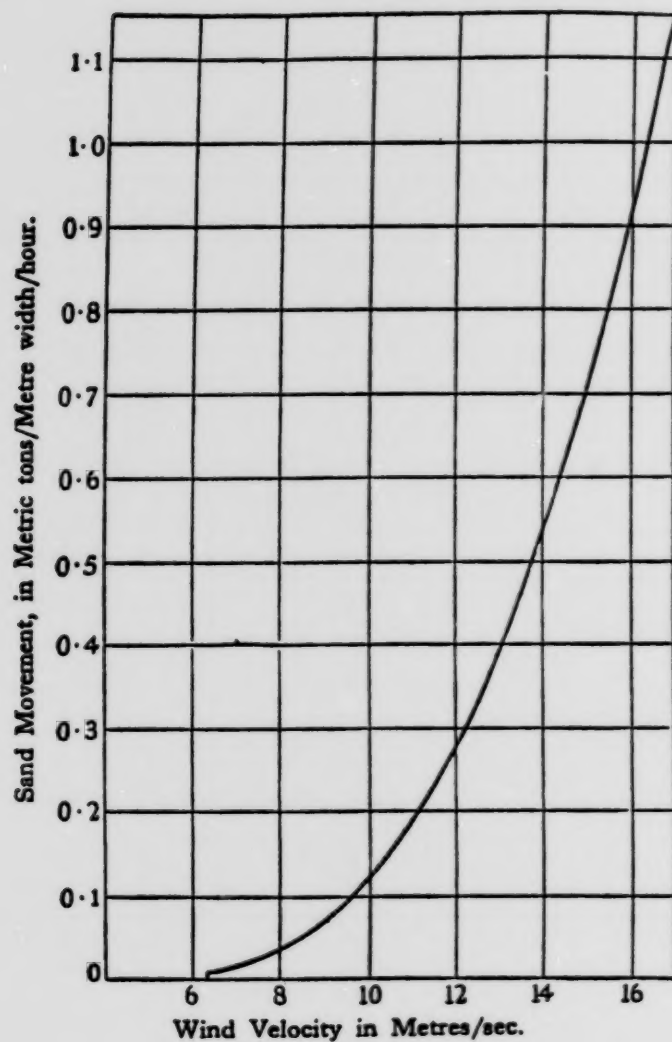


Figure 2. Relation between the flow of average dune sand and the wind velocity as measured at a standard height of one metre (53).

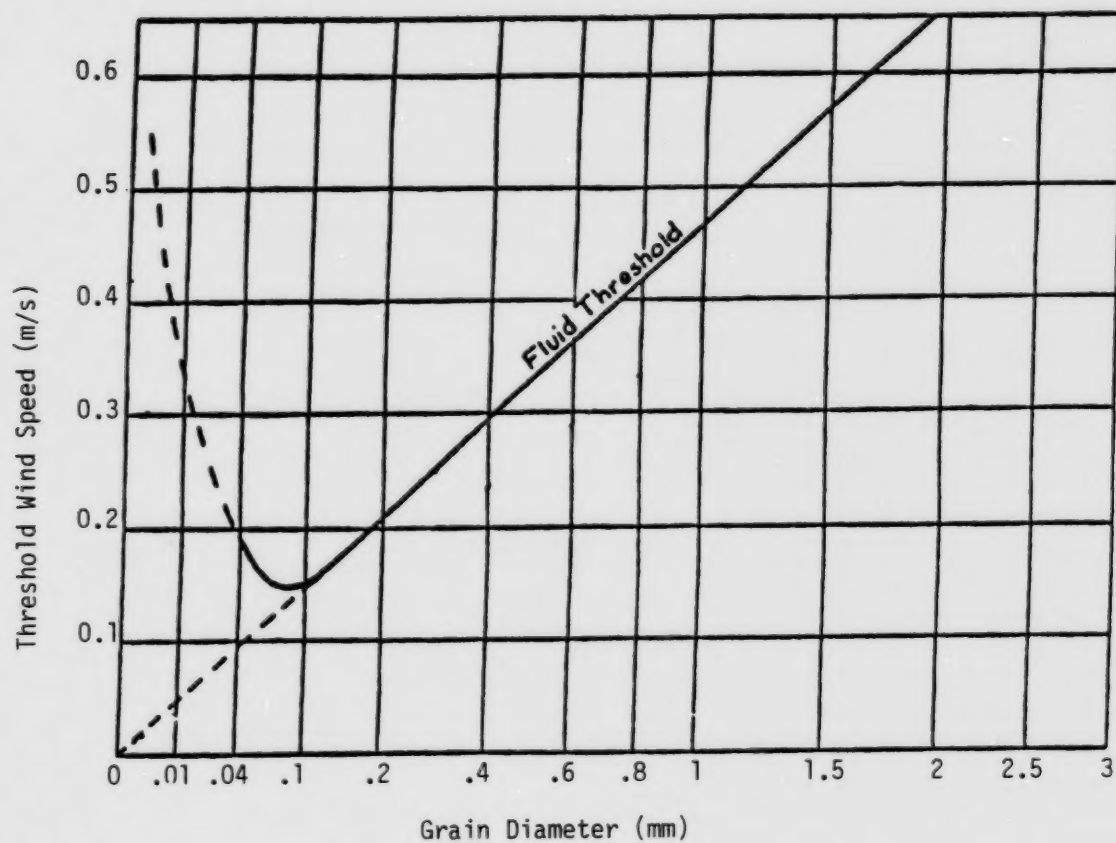


Figure 3. Particle size versus threshold wind speed (53).

Since forest cover should exist on one-third to one-half of the tailings in two hundred years, wind erosion should continually decrease until then. But for the reasons stated in the previous paragraph, a significant amount of the tailings could be transported off the site within only a few hundred years.

#### 3.4.3.3 Beaverlodge

The tailings are covered by broken rock or water. They should not be eroded by wind.

#### 3.4.3.4 Rabbit Lake

Because of the planned closeout method (see Section 5.3.3.4), wind should not erode the tailings. The only time when surface tailings may be wind-eroded will be the one and one-half year period (in the late 1980's) between the draining of the water cover and the emplacement of the final cover (58). It is improbable that significant release of tailings could occur during that period.

If rip-rap is not used on the embankments, high winds may cause blowouts in them before vegetation protection is adequate. This may occur during the next several decades.

#### 3.4.3.5 Key Lake

The closeout method that will probably be used (see Section 5.3.3.5) is designed to reduce wind erosion.

### 3.5 CONCLUSIONS

- The threat of wind erosion to an impoundment is countered at closeout. Wind erosion should never occur if the entire impoundment is covered by rip-rap, vegetation or water.
- Embankment blowouts are the greatest threat of high winds. Blowouts can cause embankments to fail by weakening their stability.
- Winds of regular speed should not cause embankment failure.
- Tornado winds are insignificant at all Canadian uranium tailings sites. Tropical cyclones may release small amounts of tailings from the Ontario sites. The low pressure storm systems (of the regular Canadian weather pattern) are the important source of high winds.
- In Bancroft, tailings release by high winds will probably be insignificant everywhere except at Madawaska Impoundment No. 1. That impoundment may be slightly damaged.

- Significant tailings release by high winds could occur at the Elliot Lake sites within the next several decades.
- High winds may eventually transport much of the Lorado tailings. A large portion could be moved from the site within a few hundred years.
- A large portion of the Gunnar tailings could be transported from the tailings pile within a few hundred years. Wind erosion problems already exist there. The rate of erosion should decrease until two hundred years from now, when it is estimated half the tailings will be forested.
- Tailings wind erosion is considered to be insignificant at Rabbit Lake. However, embankment blowouts may occur in the next several decades.
- At Beaverlodge wind erosion is likely to be insignificant.

## 4. EARTHQUAKES

### 4.1 EARTHQUAKE EFFECTS

Earthquakes release radionuclides to the environment in three ways: through embankment instability and consequent failure, through liquefaction and consequent spread of tailings, and through cracking and disruption of the tailings cover and/or liner.

Earthquake damage decreases in severity with time after closeout. Appendix B contains the Richter and Modified Mercalli Scales, which classify earthquakes.

#### 4.1.1 Liquefaction

Severe seismic shock can liquify most tailings because of the way they are deposited. Liquefied tailings are a fluid of high unit weight and zero shear strength (59). The fine materials in the interior of tailings dams are prone to liquefaction during earthquakes. The downstream slope of the embankment, often made of saturated, loosely deposited sands, can also liquefy.

Massive liquefaction failure will occur only if tailings are at or near saturation; however, a few hundred years after closeout, the spread of tailings through liquefaction is impossible because the water content of the tailings is reduced by seepage, evaporation, and planned drainage (4).

#### 4.1.2 Embankment Failure

An embankment will probably fail if it is subjected to an earthquake stress greater than the design stress. The chance of failure from earthquakes decreases with time after closeout. It is directly proportional to the tailings volume and water content. The higher the embankment, the greater the destructive effect of the lash caused by the quake's horizontal amplitude.

Slope failure can occur through embankment liquefaction (partial or complete) or through cracking and fissuring of the dam. These have often occurred together. Radionuclide dispersion is not serious in slope failures without tailings liquefaction, since a small amount of tailings is released to the environment.

#### 4.1.3 Cover and Liner Damage

Cover and liner damage is usually less serious than the latter two since it does not quickly spill many tailings. However, in the long-term, it can release a great amount of radionuclides because the release is continuous. Radon emanation and gamma ray radiation are increased when the cover is cracked. Liner damage can result in



unacceptable levels of radionuclide transport through the groundwater pathway. An earthquake-induced failure of the liner or foundation that results in increased seepage rates can be as serious as a liquefaction failure (4). Tailings mass instability is increased by the erosion occurring after cover and/or liner damage.

#### 4.1.4 Differential Settlement

Ground settlements resulting from ground shaking during earthquakes are rarely uniformly distributed and cause differential settlements in structures which can be a major cause of damage (60). Cover, liner and embankment failures resulting from differential settlement may cause radionuclide release. Unlike the danger of tailings liquefaction, earthquakes can cause differential settlement at any time.

### 4.2 THE BARAHONA AND EL COBRE DISASTERS

The hazard posed by earthquakes to mill tailings is well illustrated by two Chilean tragedies.

An earthquake destroyed the Barahona Dam of the El Teniente Mine on December 15, 1928. The earthquake lasted 1 minute 40 seconds; the dam gave way about 3 minutes after the quake began (61). The dam was destroyed because a wall in its upstream centre, sank. Fifty-four people were killed (61).

The La Ligua earthquake of March 28, 1965, caused the failure of some tailings dams containing wastes from mining operations. The El Soldada Mine, in the village of El Cobre, was one of them. Its contents turned into a viscous liquid and then flowed down a valley travelling seven miles (11 km) in a few minutes (62). A town adjacent to the dam was buried. The dam was located twenty-five miles (40 km) from the earthquake epicentre. Eleven dams were destroyed totally or partially during this earthquake (62).

### 4.3 CANADIAN TAILINGS SITES

Figures 4 and 5 present probability estimates of seismic motion for the whole of Canada. The maps are based on estimates derived from Canada's relatively short documented history of earthquakes and express a probability that a larger-than-estimated ground motion will occur within a given time period (63).

#### 4.3.1 Saskatchewan

Figures 4 and 5 show that Saskatchewan uranium tailings are safe from earthquakes. Earthquakes will never affect them. All engineering reports written for the uranium mining companies conclude the same.

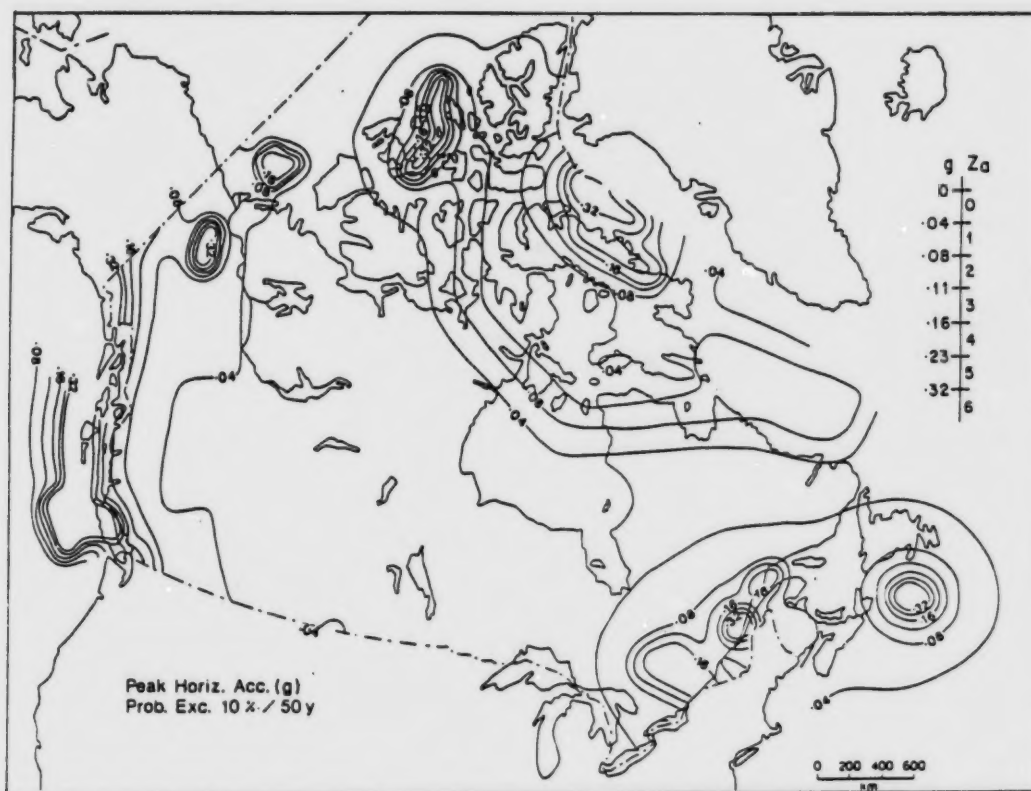


Figure 4. Peak horizontal acceleration with a probability of exceedance of 10% in 50 years (63).

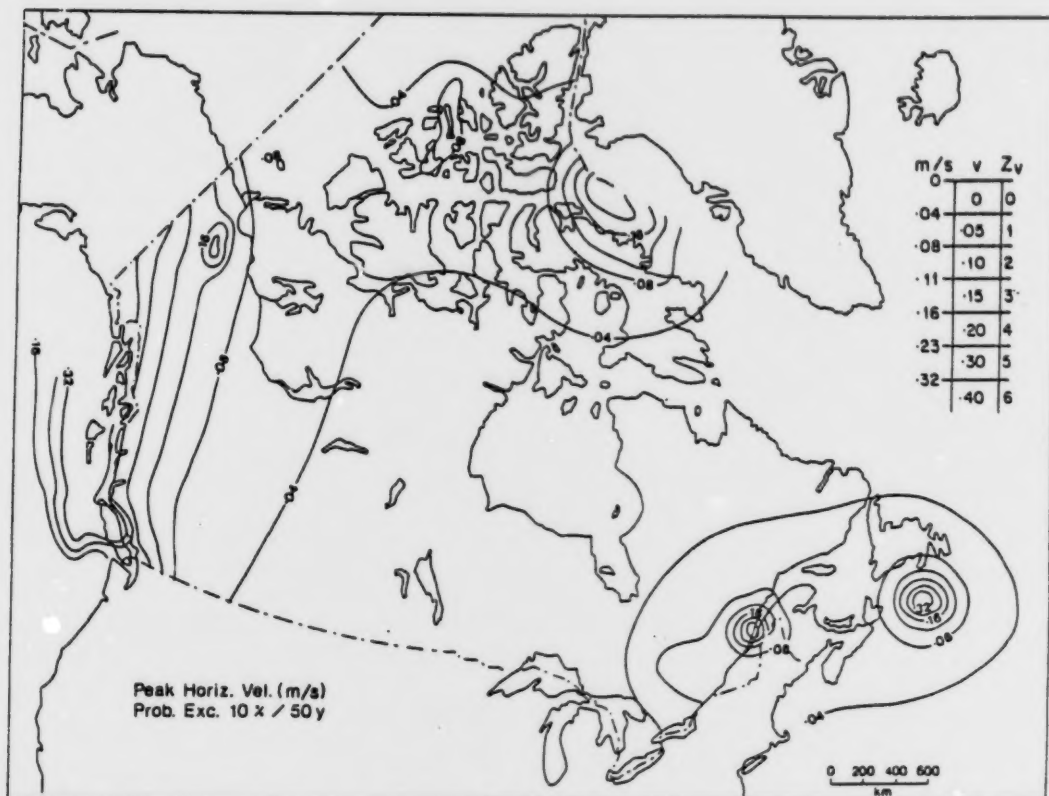


Figure 5. Peak horizontal velocity with a probability of exceedance of 10% in 50 years (63).

#### 4.3.2 Elliot Lake

Seismic activity is low, but not negligible. The Elliot Lake area is outside the four most active seismic zones in Eastern Canada and the adjacent United States (23). The "Maximum Credible Earthquake" is of magnitude 7.0 on the Richter Scale. It is located 225 km from Elliot Lake in the "Western Quebec" zone. It is predicted that this event would cause an intensity of IV, on the Modified Mercalli Scale, at Elliot Lake, with a corresponding peak ground acceleration of 0.065 g. The duration of shaking would be less than 20 seconds (23).

At the Quirke tailings site, stability analyses were made on two existing dykes, Dyke No. 2 and the East Dyke. They are considered to be representative elements of the existing and proposed internal stacking program that will last until closeout in 1991 (64). On the basis of both static and dynamic analyses, it is indicated that there is an adequate factor of safety against failure (64).

Earthquake effects could be worsened by the network of the dams, tailings and watershed of the Serpent River basin. For example, a flow of liquefied tailings can travel downstream to intercept tailings ponds, natural lakes, and even other tailings flows; a "snowballing" flow could result.

However, all studies indicate that there is little chance of earthquake-induced embankment failures in the short-term. One study found that an earthquake is a very unlikely event, and liquefaction of tailings would be an "incredible event", one which would not occur in the opinion of the experts (65). Other analyses indicate that some of the tailings can liquefy during a peak ground acceleration of 0.065 g, and that they would be retained by perimeter embankments (64).

Long-term predictions are less confident. It was found that the Ministries of Natural Resources and Labour have no definitive criteria for evaluating the construction, materials used, and stability of tailings dams (65). Seismic stability of the majority of dams and dykes on the Denison and Rio Algom properties was unknown in February, 1978 (65).

In the long-term, it is possible that an earthquake could damage the Elliot Lake impoundments.

#### 4.3.3 Bancroft

Seismic activity is slightly greater at Bancroft than at Elliot Lake. However, in 1981, there were 45 times more tailings at Elliot Lake than at Bancroft; there may eventually be 100 times more at Elliot Lake (1). Therefore, the risk of radionuclide release from earthquakes is less at Bancroft than at Elliot Lake.

#### 4.3.4 The Ontario Sites in General

Dam breach by liquefied tailings releases tailings and radionuclides to the environment in the fastest way possible. But in Ontario, it will not be an important cause of release. A major earthquake is more likely to crack the cover and/or liner or destabilize the embankment slopes (4). Destruction of dykes and embankments and the displacement of tailings by earthquake-induced slides and slumping will probably not occur at the Ontario sites because the landforms are too stable.

The effect of many small tremors over the long-term must be considered. Such a series of quakes can cause differential settlement in the cover and/or liner (66). There is probably a site-specific threshold magnitude below which no quake, or series of quakes, will disturb the impoundment (66, 67).

#### 4.4 EARTHQUAKE RECORD 1968-81

An appreciation of the seismic activity in the very short-term at the three general tailings sites is gained by a look at the data from the complete earthquake record for Canada and adjacent areas, for 1968-81 (68). All magnitudes are from the Richter Scale.

Table 4 gives estimates of duration of strong earthquake motion (69). They apply to earthquakes in general (69).

| Distance<br>(km) | Magnitude (Richter Scale) |     |     |     |     |     |     |
|------------------|---------------------------|-----|-----|-----|-----|-----|-----|
|                  | 5.5                       | 6.0 | 6.5 | 7.0 | 7.5 | 8.0 | 8.5 |
| 10               | 8                         | 12  | 19  | 26  | 31  | 34  | 35  |
| 25               | 4                         | 9   | 15  | 24  | 28  | 30  | 32  |
| 50               | 2                         | 3   | 10  | 22  | 26  | 28  | 29  |
| 75               | 1                         | 1   | 5   | 10  | 14  | 16  | 17  |
| 100              | 0                         | 0   | 1   | 4   | 5   | 6   | 7   |
| 125              | 0                         | 0   | 1   | 2   | 2   | 3   | 3   |
| 150              | 0                         | 0   | 0   | 1   | 2   | 2   | 3   |
| 175              | 0                         | 0   | 0   | 0   | 1   | 2   | 2   |
| 200              | 0                         | 0   | 0   | 0   | 0   | 1   | 2   |

TABLE 4. Duration of ground motions (seconds) (acceleration > 2 Hz) versus magnitude and distance from fault rupture (epicentre) (69).

#### 4.4.1 Saskatchewan

The epicentre of the closest earthquake of magnitude (m),  $3 < m < 4$ , was 300 km from the centre of the uranium mining region and all others were at least twice as distant. The epicentre of the closest quake of magnitude  $4 < m < 5$  was 700 km away; there was an average of one per year at a distance of 900-1250 km. Resultant ground motion at the tailings sites was negligible.

#### 4.4.2 Elliot Lake

The closest quake of  $3 < m < 4$  was 125 km away and at least two each year were within 725 km. The closest  $4 < m < 5$  quakes were 375-725 km away. It is not known whether any tremors were felt from the closest  $3 < m < 4$  quake. There were no effects from the others.

#### 4.4.3 Bancroft

There was a large concentration of  $3 < m < 4$  quakes 125-250 km away. About one  $4 < m < 5$  quake occurred 200-675 km away every two years. Seismic activity at the tailings sites reached III on the Modified Mercalli Scale (Appendix B).

#### 4.5 CONCLUSIONS

- The risk of an earthquake-induced failure of a uranium tailings impoundment is negligible only in Saskatchewan. Such a failure is more probable in Elliot Lake than in Bancroft.
- Differential settlement could probably cause the failure. It would allow slow release of radionuclides through a damaged cover, liner or embankment. It may occur anytime.
- Dam breach by liquefied tailings would cause the most dangerous release. It is improbable at the Ontario sites. It may occur in the next few hundred of years only.



## 5. FOREST FIRES

### 5.1 NATURAL VEGETATION OF TAILINGS LOCATIONS

The natural vegetation of the three uranium tailings areas is forest.

The forest of the Bancroft area is a mixture of broadleaf and needleleaf trees. It is in the zone of mixed forest called the Great Lakes-St. Lawrence Forest Region. The forest is transitional between the boreal to the north and the deciduous to the south. It comprises sugar maple, yellow birch, hemlock, black and white spruce and white pine.

The Elliot Lake area lies in the same forest zone as Bancroft, but in this area there is more fir and less white pine and hemlock. This is because it is closer to the southern limit of the boreal forest.

All of the northern Saskatchewan sites lie within the boreal forest zone. Here, black and white spruce, jack pine, tamarack and white birch predominate. The Uranium City area and the shore of Wollaston Lake are near the northern limit of the boreal forest. In these locations are also found open woodland with a lichen floor, spruce and tamarack trees.

### 5.2 FIRE EFFECTS AND SIGNIFICANCE

The detrimental effects of forest fire are explained by Shepherd (Appendix A). These direct effects of vegetation loss on an impoundment - erosion and runoff increase - are the only ones of concern. This is because:

1. A vegetation cover does not decrease the rate of radon emanation from uranium tailings (70).
2. It does not prevent pyrite oxidation (71).
3. The effects of a vegetation cover on the hydraulic properties and hydrological conditions of the tailings are unknown (72-75). For example, its effect on water movement and its impact on the quality of runoff and seepage have not been established. Hence, its effects are not necessarily important.

There is one other possible bad effect of fire. It could strike an impoundment within 50 years after revegetation by man. The help that the cultivated vegetation gives to the growth of native vegetation could be partly lost.

Burning of forests on shallow soils can be followed by serious erosion and consequently cause a very prolonged recovery period (76). This may be partly due to decreased water infiltration rates on burned-over soils which has been found by many (77).

Another study found no change in infiltration rates from unburned soils to burned-over soils (77). Erosion was not serious and destruction of plant cover, litter and organic matter did not result in more than light sheet erosion. Gully erosion was noted only twice. Rain pelting on exposed soil caused little or no surface runoff. Wind erosion, which formed small sand dunes, was not considered a serious factor in soil loss. This study was done in Saskatchewan's Black Lake region. The Black Lake region is close to all the northern Saskatchewan tailings sites and is in the same forest zone as the sites. Therefore, the results of this study may be truer at the Saskatchewan tailings sites than the results of the previous studies.

In Alaska, Lutz also found erosion "surprisingly small" (77).

Studies show that the effects of fire on soil properties vary widely with soil type, climate, vegetation and severity of burn (78). For that reason, the effects at Canadian tailings sites cannot be generalized. But there are two effects that are always true and they are of particular interest concerning tailings. The first is that soil acidity is decreased as concluded in all the literature. This is significant on tailings where acid generation kills vegetation. Decreased acidity may last for up to 25 years (77). The second is that the soil nutrient level is increased, and this too is a conclusion reached in all the literature. This is significant because tailings lack nutrients. The effects of fire on forest soils are favourable to certain soil properties and unfavourable to others (77). It is beyond the scope of this report to find whether or not the bad effects exceed the good ones.

### 5.3 REVEGETATION OF TAILINGS SITES

Before forest fires are a threat, tailings must be revegetated. Amount and speed of future growth must be assessed. Revegetation can occur either with human aid followed by natural encroachment, or through natural encroachment only. It is generally assumed that both seeded and natural vegetation will eventually form the basis of a self-sustaining ecosystem on the tailings (79-81).

It will take four or five years to allow for weathering, settlement, and acid correction before vegetation can be established on a tailings site. Another ten years is usually required to develop a suitable soil and plant structure to permit lumber-grade trees to be grown. In five years, vegetation could be comprised of 20 per cent trees and 80 per cent grasses, while in ten years, there could be 90 per cent trees and 10 per cent grasses (82).

### 5.3.1 Bancroft

No attempt has been made to revegetate the tailings. Nevertheless, they all have a good cover of natural vegetation (Table 5). The exception is Madawaska Impoundment No. 1 (operated until 1982), where the tailings are covered with waste rock and gravel. The cover should hasten natural revegetation, compared to revegetation on bare tailings. The natural vegetation will probably encroach on this pond as on Madawaska Impoundment No. 2 (83).

The advantage of a rock cover is that it improves plant growth conditions. Moisture retention is held more closely to a constant level; shelter from windblasting by fine tailings is improved, wind transport of tailings is reduced, organic matter is trapped in spaces between rocks to form a soil and the temperature range in the spaces between the rocks is reduced (the spaces are a relatively mild microclimate).

Bancroft tailings are not acid-generating. They are relatively moist, and have small surface areas (79). Consequently, they are better vegetated than any of the other tailings sites. Trees, shrubs and cattails are already common on them. The Bancroft tailings will probably be fully forested within a hundred years. More information on Bancroft is included in the following section.

### 5.3.2 Elliot Lake

A recent study of the Bancroft and Elliot Lake tailings makes conclusions on the revegetation success in both the wetland and dryland tailings environments (84). The conclusions are the same for Bancroft and Elliot Lake:

- Cattails grow equally well on the tailings as in the wild.
- Wetland communities are stable and are under no serious environmental stress.
- Trees of the dryland environments on the other hand are growing at their limits of ecological tolerance and stand development differs much from that observed in normal forests.

Attempts have been made to vegetate almost all the inactive tailings at Elliot Lake. The success achieved has been possible only because of the large investment in improving the soil environment and in accepting a low level of productivity from the biological system, i.e. accepting a low rate of survival and reseedling (73). It would be inaccurate to describe the tailings as anything but a hostile environment for plant life. Wind erosion is a problem on the Elliot Lake tailings sites (85). Also, the tailings are very acidic.

| Name of tailings site     | Dry surface area (ha) | Operation of tailings (a) | Year amendment initiated | Amendment measures      | Seeding mixtures  | Estimated area with vegetation <sup>1</sup> (%) | Comments                                                        |
|---------------------------|-----------------------|---------------------------|--------------------------|-------------------------|-------------------|-------------------------------------------------|-----------------------------------------------------------------|
| <u>Bancroft Area:</u>     | 25                    |                           |                          |                         |                   |                                                 |                                                                 |
| Madawaska                 | 16                    | 1957-1964                 | 1978                     | waste rock overburden   | grass & legumes   | 80                                              | -3/4 of site covered, sampled only from exposed tailings areas. |
| Auger Lake                | 2                     | 1957-1963                 | unamended                | -                       | none              | 70                                              | -vegetation belts on beaches & forest edge.                     |
| Bicroft Proper            | 4                     | 1956-1957                 | unamended                | -                       | none              | 50                                              | -bare areas in centre of site.                                  |
| Dyno                      | 3                     | 1957-1960                 | unamended                | -                       | none              | 90                                              | -3/4 of site wetland not sampled.                               |
| <u>Elliot Lake Area:</u>  | 248                   |                           |                          |                         |                   |                                                 |                                                                 |
| Williams                  | 2                     | 1959 <sup>2</sup>         | 1976                     | glacial till top soil   | grasses & legumes | 100                                             | -tailings beach, cattail stand.                                 |
| Nordic                    | 101                   | 1957-1968                 | 1970                     | neutralization          | grasses & legumes | 80                                              | -roadways of waste rock on site.                                |
| Crotch                    | 53                    | 1957-1964                 | 1970                     | neutralization mulching | grasses           | 30                                              | -extensive bare areas, experimental plots with vegetation.      |
| Stanrock Main             | 63                    | 1958-1964                 | 1978                     | neutralization          | none              | 20                                              | -extensive bare areas, moist areas vegetation.                  |
| Olive                     | 5                     | 1958-1959                 | 1977                     | neutralization          | grasses & legumes | 80                                              | -tailings beach, cattail stand.                                 |
| Lacnor                    | 24                    | 1957-1960                 | 1978                     | neutralization          | grasses & legumes | 80                                              | -roadways of waste rock on site.                                |
| <u>Uranium City Area:</u> |                       |                           |                          |                         |                   |                                                 |                                                                 |
| Gunnar Main               | 45                    | 1955-1964                 | unamended                | -                       | none              | 60                                              | -moist areas dense vegetation, cattail stands.                  |
| Langley Bay               | 11                    | 1954-1964                 | unamended                | -                       | none              | 60                                              | -tailings beaches, denser vegetation.                           |
| Gunnar Central            | 12                    | 1955-1964                 | unamended                | -                       | none              | 70                                              | -denser vegetation on forest edges.                             |

<sup>1</sup> based on aerial photographs, flights in 1973 for Elliot Lake, Bancroft 1977 and Uranium City 1976  
<sup>2</sup> spillage  
<sup>3</sup> estimate does not reflect ± vegetation cover

TABLE 5. Site history and descriptions of abandoned or inactive uranium mill tailings (79).

Almost all revegetation attempts have used the method of limestone and fertilizer application followed by direct seeding onto the tailings surface. It is not very successful at quickly establishing a good vegetation cover; this is evident from maps and photographs (21, 86). Revegetation attempts have resulted in patchy growth at best, and some of the growth has eventually died from acid-kill, drowning, drought, tailings windblast or a combination of these. At present, the vegetation on most of the tailings is an inadequate cover. It has a tenuous hold on survival.

A method has been developed that establishes an excellent self-sustaining vegetation cover with a promising soil profile in only five years. It involves application of limestone at 20-67 tonnes/hectare and fertilizer at 200 kg/hectare; mixing the top 15 cm of tailings with the limestone and fertilizer; seeding the area; and dressing the top with maintenance fertilizer at 600 kg/hectare/year for five years (87). On a three-acre test plot, conifer seedling success rates and growth were better than in a natural forest (80).

The mining companies are required by Ontario law to stabilize tailings with a vegetation cover as soon as possible after the tailings sites become inactive. If the above five-year method is used at all, it is not always applied consistently and correctly. But even limestone neutralization only -- the minimum tailings treatment -- ensures the encroachment of the surrounding forest (80). Some tailings fines -- the most hostile tailings to plant life -- are supporting poplar trees 3-4 years after limestone application (73). Whatever method is used, the quality of the vegetation cover will improve once the tailings are stabilized (80); however, there is little chance that Elliot Lake tailings (unlike Bancroft's) will support a vegetation cover without any amendment.

In summary, if a good revegetation method is used, and applied consistently, the cover on the tailings will be like the surrounding forest between one to two hundred years after closeout (80, 81). An exception would be the extent of soil profile development; it would be less on the tailings. But for at least a few decades after closeout of any Elliot Lake tailings impoundment, its vegetation cover will range from poor to just sufficient for erosion protection. This has been the case so far.

### 5.3.3 Saskatchewan

#### 5.3.3.1 Lorado

The tailings have never supported vegetation, no natural encroachment has occurred and no revegetation attempts have been made. The tailings are very acidic (5 per cent sulphur content), and have a high lead level (56).



They are heavily eroded by wind and water (86). Because of these characteristics, and the fact that no amendment of the site is planned, vegetation will probably never grow on the tailings. Some tailings, less hostile to plant life, have not supported natural vegetation since closeout, forty to fifty years ago (88). Therefore, the Lorado tailings are considered to have an insignificant forest fire risk.

#### 5.3.3.2 Gunnar

The tailings have not been amended (Table 5). Although they are neutral, natural vegetation has established itself slowly. One-third of the tailings are bare and windblown, which will not change if left unamended (80). The other two-thirds of the surface has some vegetation cover. Some of this is lush 100 per cent cover, but the majority is thinly-spaced grass hummocks (56).

It can be concluded that at least one-third of the Gunnar tailings surface should always be bare. Also, one-third to one-half will likely be forested in about two hundred years.

#### 5.3.3.3 Beaverlodge

The tailings are covered with either water or broken rock. Fire cannot affect those with water cover. The rock-covered tailings will probably be forested in about two hundred years.

#### 5.3.3.4 Rabbit Lake

The tailings impoundment is being closed-out. Waste rock or compacted till with waste rock on top, will probably be used as the cover; it could be over a metre thick. Embankment slopes will at least be revegetated; rip-rap with hydroseeding may be used (89).

The cover will provide a good to excellent growing habitat (90), and the embankment slopes should too. Therefore, the impoundment will probably be fully forested in two hundred years. The reason why this much time is needed when similar conditions in Bancroft require about a hundred years for forestation, is that growth is relatively slow at the latitude of Rabbit Lake.

#### 5.3.3.5 Key Lake

The probable closeout method is as follows. The embankments will be faced with rip-rap. The cover will be a 300 mm gravel capillary break overlain by 300 mm of a clay-till mixture, and further overlain by a yet unknown material (88).

For the same reasons as at Rabbit Lake, the impoundment will probably be fully forested in two hundred years.



## 5.4 FOREST FIRE STATISTICS

### 5.4.1 Fire Causes

Man and lightning are the two causes of forest fires. The effect of lightning will not change for at least the next few thousand years. However, man's role in forest fires cannot be predicted past about a hundred years from now.

In the Caribou Range of the Northwest Territories, lightning accounts for 97 per cent of the total area burned. With few exceptions, man-caused fires have been small (91). The Caribou Range is centred 160 km north of Uranium City and, therefore, these statistics are true for the tailings sites near Uranium City (Gunnar, Lorado, Beaverlodge). They may apply to the other northern Saskatchewan tailings sites as well. For the ten-year period, 1970-79, lightning caused 45 per cent of Saskatchewan's forest fires and 86 per cent of the area burned.

In the Bancroft and Elliot Lake regions, more than 90 per cent of the area burned is burned by man-caused fires (93). These regions have by far, the greatest number of man-caused fires in the province, but they are relatively small due to firefighting efforts (93).

### 5.4.2 Periodicity

The following information shows that 75 years is a good time interval to expect between fires at the Bancroft and Elliot Lake sites (94). Swain and Heinselman found natural fire recurrence periods in the Great Lakes - St. Lawrence Forest Region of Minnesota to average 60-70 and 100 years, respectively. Owynar found a natural recurrence period of 70 years in a portion of Algonquin Park. In general, research in the Great Lakes - St. Lawrence Forest Region shows that a fire recurrence interval of 75 years was most typical before firefighting programs were organised (94).

Fire is an integral part of the subarctic and it reoccurs in a probabilistically consistent manner. It is neither unorderable, infrequent nor external to the subarctic ecosystem (95). Data presented indicates a recurrence interval of 110 years in the boreal forest north of the Saskatchewan sites (94). Therefore, assuming that the recurrence interval decreases with decreasing latitude, fire can be expected at each Saskatchewan tailings site at least every 110 years.

The notion of regularities in the occurrence of large fires is supported by Wright and by Boulton (96). Wright suggested that there is a connection between the sunspot cycle and the incidence of forest fires in New Brunswick. Boulton found evidence of a regular pattern in the occurrence of large rural fires in Ontario.

The above evidence shows that fire will probably occur regularly and often, beginning when an impoundment is reforested.

#### 5.4.3 Sites

##### 5.4.3.1 Bancroft

The tailings are in a forest fire occurrence zone of 6-8 man-caused fires/1000 km<sup>2</sup>/year, and 0.5-1 lightning-caused fires/1000 km<sup>2</sup>/year (97). Compared to the rest of Ontario, Bancroft ranks highly in forest fire occurrences. However, fire detection and fighting are more efficient in the Bancroft area than in most of Ontario, especially northern Ontario.

For the period 1921-1976, 32 forest fires of at least 200 ha occurred within 50 km of Bancroft. They were almost evenly spread around the town. One occurred in 1949, another in 1946 and all the rest in the 1920's and 1930's (98).

Forest fire information is also available for a rectangular area, 20 km by 14 km, centred 2 km west of Bancroft (99). The Madawaska impoundments lie within it; the other tailings lie just southwest of it. During the years 1965-84 inclusive, 60 ha -- 0.2% of the area -- was burned by forest fires.

##### 5.4.3.2 Elliot Lake

The tailings are in a forest-fire occurrence zone of 4-6 man-caused fires/1000 km<sup>2</sup>/year, and 1-2 lightning-caused fires/1000 km<sup>2</sup>/year (97). These are slightly higher occurrences than those in most of Ontario. For the period 1921-1976, 44 forest fires of at least 200 ha occurred within 50 km of Elliot Lake; they all occurred between the years 1922-1955 inclusive (98). Note that one-fifth of the area within this radius is in Lake Huron. Many of these fires were as large as the largest Bancroft area fire during the same period, and some were two to seven times larger.

Information is also available for a 20 km by 14 km area centred near the town of Elliot Lake. It contains almost all the tailings sites with the Quirke and Strike Lakes tailings sites 1-2 km north of it. From 1965-1984 inclusive, 35 ha -- 0.13% of the area -- was burned by forest fires.

##### 5.4.3.3 Saskatchewan

The forest of the tailings sites is in the secondary protection zone of Saskatchewan's forest fire control. In this zone there is no active suppression unless fire can be put out with minimum expenditure (100). One-third to one-half of Saskatchewan north of 56 1/2°N latitude was burned by forest fires in the period 1963-1984 (101). For that region, that is the usual amount of burning for a 20-year period (100). The tailings are all located in that region.

The Caribou Range Forest District is centred 160 km north of Uranium City. The district has an area of 106 000 km<sup>2</sup>. For the eight year period, 1966-1973, an average of 0.9 per cent of the district burned each year (91). The amount of burning is estimated to be similar at the tailings sites because of their proximity to the district.

#### 5.5 POST-FIRE VEGETATION

All the literature indicates that in natural forest conditions, regrowth of a cover of greenery after a forest fire is swift. However, a long time may be needed for the greenery to grow into a mature forest. In northern Canada, the recovery period from vegetation on a burn to climax vegetation is a lengthy process. Short summers, low precipitation, and shallow soil all combine to slow plant succession (78).

In the northeastern Minnesota forest, a forest region similar to that of Elliot Lake and Bancroft, the rate of growth in burned areas is strikingly rapid. There is marked lushness in size, color and thickness of leaves of many species in the first few post-fire growing seasons (102-103).

Studies done in northern Canada conclude the following:

- Fire is a natural and integral part of the subarctic ecosystem. The adaptation of this ecosystem to disturbance by fire is demonstrated in the combination of species of different life histories. This combination of life histories allows a flexible response on the part of the ecosystem to different frequencies and intensities of fire (95).
- If it is accepted that fires have always been an intrinsic part of northern ecological systems, then the plant communities must be in some sort of adjustment to fire, able to survive its effects and very likely deriving benefits from it (91).

In this paragraph, a description of the relationship between fire, vegetation and erosion is given (104). True soil erosion following forest fire on the Canadian Shield in the boreal and Great Lake-St. Lawrence forest regions, is a very minor consideration because most of the forest does not erode after fire. These forest regions, having burned and regrown about a hundred times since the last glacial retreat, have come into equilibrium with the erosional processes. The situation on tailings is somewhat different because the tailings do not present natural conditions. For instance, the impoundment embankments would be prone to erosion. However, erosion will not be a problem where a strong root system has been established by vegetation which reproduces vegetatively (e.g. grasses and poplar trees). Even if all the litter and duff were removed to expose the mineral soil which had formed since tailings closeout, the root system would hold everything together, and vegetation would be plentiful within a year (104).

It seems then that fire poses little erosion threat to forested tailings.

## 5.6 CONCLUSIONS

- Bancroft tailings will probably be forested in one hundred years.
- Elliot Lake tailings will be forested between one to two hundred years from now if vegetation is done properly by man; unamended tailings will not support a vegetation cover until the surface layer has been leached of sulphides and other toxic materials.
- So far, at Elliot Lake, only limited measures have been taken to permanently stabilize the impoundments with vegetation.
- Vegetation will probably never grow on the Lorado tailings. (unless some remedial work is done)
- Vegetation will probably never grow on one-third of the Gunnar tailings. One-third to one-half of the tailings may be forested in two hundred years.
- Beaverlodge, Rabbit Lake and Key Lake tailings will likely be forested in two hundred years.
- Forest cover on tailings should always grow back after a fire.
- Forest covers could be burned regularly and often during the lifetimes of the impoundments.
- Forest fires pose little threat of radionuclide release from tailings impoundments.

## 6. CLIMATIC CHANGE

The earth's climate is not fixed. It changes continuously with time and location (16). Unlike the natural events previously discussed, climatic change requires years to materialize and it does not end after minutes, days, or even weeks. Evidence suggests that climatic cycles occur regularly, varying from relatively very minor 30-year cycles to major glacial and interglacial cycles of tens to hundreds of thousands of years (16).

It is not known where the world climate is heading. The weather of Canada in several years or its climate a few centuries from now is unknown (105). Meteorologists do not yet know enough about atmospheric processes to attempt successful long-range climatic forecasts. Nor can climatological data series be confidently extrapolated, since contemporary geophysical data are not necessarily representative of much longer periods (105-106).

It is questionable whether man has actually altered the world climate. However, his influence may rival or overrule natural climatic changes early in the twenty-first century or maybe even sooner (105).

The changes most likely to affect Canadian uranium tailings are glaciation, drought and the carbon dioxide (CO<sub>2</sub>)-caused greenhouse effect. These changes are examined separately in the following sections.

### 6.1 GLACIATION

#### 6.1.1 Effects on Tailings Impoundments

The movement of even a small glacier would trigger several other failure mechanisms of a tailings impoundment. Blockage or destruction of diversion canals could cause a failure due to overtopping, erosion and/or flooding. The weight of the glacial ice could cause differential settlement and/or embankment instability. All vegetation could be destroyed, leaving any remaining tailings subject to erosion by wind and water. Because of the magnitude of the forces associated with glaciation and the related failure mechanisms that could occur due to a glacier, it is very doubtful that any portion of a tailings impoundment could survive even a small, relatively short-term glaciation (4).

The magnitude of release of tailings due to glaciation would depend on the location of the impoundment relative to the forward edge of the glacier. If the edge did not reach the impoundment, water released by the glacier could be diverted around the impoundment without the release of tailings. If the glacier moved onto or past the impoundment, the entire impoundment would probably be released by one



of the failure mechanisms mentioned in the previous paragraph (4). After demolishing an impoundment, a glacier could spread tailings over a huge area. Glaciers can transport large amounts of material en masse for hundreds of kilometres. Also, their meltwaters are powerful agents of transport and deposition of this material.

#### 6.1.2 Past and Future Occurrence

Some general characteristics of climate in the past suggest that an ice age is imminent (16):

- The last 10 000 years are abnormal in the sense that such interglacial climates represent only about ten per cent of the climate of the last 1 000 000 years.
- Climatic changes during the past 20 000 years are as severe as have occurred in the past 1 000 000 years.
- Interglacial ages each lasting 10 000 + 2 000 years and each followed by a glacial maximum have occurred on the average every 100 000 years during at least the past 1 000 000 years. The present interglacial age has already lasted 10 000 years.

From a purely statistical point of view, it is very likely that a new ice age is on its way (107). The next glaciation could possibly begin within a few thousand years although there is a finite probability that a serious worldwide cooling could occur within the next 100 years (16). The probability of a transition in the next 100 years to the type of climate leading to an ice age is less than one per cent (106). The probability of onset within the next 1 000 years of glacial climate associated with the 100 000-year glacial-interglacial cycle is about two per cent (108).

Extrapolation of the paleoclimatic record into the future indicates a long-term downward trend in global temperature with successively more severe cooling peaks at 5, 23, and 59 millenia from now (109). The present Pleistocene glaciation is expected to last for another hundred million years (110). These two points suggest that many glacial ages may occur within the next several million years. Experiments suggest that ice-sheet growth in the northern hemisphere is likely to occur in about 50 000 years (107).

#### 6.1.3 Summary

Major climatic changes tend to occur rather rapidly, with transition from a glacial to non-glacial climate, and vice versa, perhaps taking less than a century (111, 112). The initiation of a new glacial phase has occurred at least eight times during the last million years (106). The occurrences may continue as regularly as before, but no one knows. If they do, glaciation would be the principal erosional force affecting both surface and sub-surface tailings (16).



## 6.2 DROUGHT

### 6.2.1 Definition

The definitions of drought are numerous and varied because of the many activities it affects. The primary cause of drought is precipitation deficiency (113). For the purposes of this report, drought is defined as insufficient precipitation for survival of the vegetation cover on a tailings impoundment. Thus, drought prevents the vegetation's restraint of wind and water erosion. This is the threat it poses to a tailings impoundment.

### 6.2.2 Time Scale

Drought is of a short duration compared to other climatic changes. It is a climatic fluctuation, a very short-term climatic change. Fluctuations last from ten to one hundred years, and many droughts are of even shorter duration (i.e. they need not last ten years to kill vegetation). Dry spells are a normal part of climate and drought is simply the result of an abnormally severe and prolonged dry spell (114).

### 6.2.3 Past and Future Occurrence

Periods of drought are certain to occur within as short a time as several hundred years, even at the Canadian tailings sites (4). Their relative frequency and intensity, location and timing, as well as their impacts, will differ from decade to decade, but their occurrence is assured (114). Drought occurrences are ever-present in varying frequency and intensity in Ontario's climatological history and there is no reason to believe that a severe, lengthy drought will not occur again (115). The occurrence of drought, however, is presently unpredictable (116).

### 6.2.4 Effects on Tailings Impoundments

Drought may or may not last long enough to kill a tailings vegetation cover (4). An investigation into the effects of drought on uranium tailings in the western United States shows that there is a remote chance that vegetation covers will die off to the degree that vegetation in the Sahara Desert dies (4). Since the climate at the western United States impoundments is much more arid than that at the Canadian impoundments, such desertification of Canadian uranium tailings sites is impossible. Known drought effects at Canadian tailings sites are restricted to the Elliot Lake area. There, the vegetation covers emplaced by man have been partly killed by summer droughts. The amount of wind erosion of tailings has increased slightly because of the vegetation loss.

### 6.2.5 Summary

Drought will strike the Canadian uranium tailings sites many times during the period when significant radionuclides release from impoundments may still occur (within 100 000 years). Resulting erosion of impoundments and of tailings material itself, may or may not be significant. It may not occur at all.

## 6.3 CARBON DIOXIDE AND THE GREENHOUSE EFFECT

Recently, concern about world climate has been focussed on changes being wrought by man as a result of radiatively active gases emitted by his activities. These gases affect the radiation balance of the earth's atmosphere and will probably, over the next one hundred years, be responsible for a world climate warmer than any experienced during the last several thousand years (117).

### 6.3.1 Cause of the Greenhouse Effect

The earth's climate is inextricably tied to the chemical composition of its atmosphere. Nitrogen and oxygen, comprising the largest volume of the atmosphere, have very little effect on climate. However, about one per cent of atmospheric gases are strongly active in affecting the radiation balance. They allow short-wavelength sunlight to enter the atmosphere relatively unimpeded, but absorb much of the long-wave radiation emitted by the earth's surface. Some of the absorbed radiation is reradiated downward to warm the earth's surface (117).

Most important among these gases is carbon dioxide. Without the effect of the natural portion of this gas, the earth's temperature would even now be 20-30°C colder and quite uninhabitable. However, the concentration of this "greenhouse" gas is increasing, and as it does, the efficiency of the atmosphere in trapping radiation emitted from the earth's surface also increases. The consequence is a global temperature rise. This is a conclusion of all the literature (117), although one opinion to the contrary has been found (112).

### 6.3.2 The Increase in Atmospheric Carbon Dioxide Level

The rise of carbon dioxide concentration in the atmosphere is unmistakably real, and quite rapid (118). During the past 25 years, measured concentrations of carbon dioxide around the world have increased by eight per cent. Present concentrations are estimated already to be 25 per cent higher than at the beginning of the industrial revolution. The primary source of this increase is a result of burning fossil fuels such as coal, gas and oil for energy. Global deforestation also appears to be a significant cause of increased atmospheric carbon dioxide levels (117). The consensus found in all the literature is that the above activities will be responsible for a doubling of the atmospheric concentration of carbon dioxide within the next 100 years.

### 6.3.3 Future Results of the Greenhouse Effect

The degree of future temperature warming due to carbon dioxide gas is debatable. However, many studies suggest that a doubled atmospheric carbon dioxide level would result in a mean global temperature rise of 2-5°C. Such a temperature change would be greater than any observed in the last 5 000 years. Assuming the CO<sub>2</sub>-associated effect is of the magnitude predicted, the world's temperature should warm significantly (109). Recorded data of the past century indicate that so far, no temperature rise due to carbon dioxide has occurred (118, 119); predictions should therefore be treated with skepticism.

The climatic effects of increased atmospheric CO<sub>2</sub> levels will not be apparent only or even most significantly in the temperature record. Rainfall, temperature and winds should all be affected (120). There may be a tendency for higher precipitation in colder regions (121). Most scientists agree that dramatic changes in precipitation and storm patterns will probably occur. Within decades, as the greenhouse effect begins to impose itself, there should be an increase in storm activity. Scientists predict fewer winter storms of the sort experienced today, but many more violent summer storms producing strong winds and tornadoes (112).

Two models of CO<sub>2</sub>-caused climatic change predict some effects in Canada. In the first model, a doubled atmospheric concentration of carbon dioxide will cause the average winter temperature to rise. The rise will be about 2.5°C for Saskatchewan tailings sites, and from 2.5-5°C for Ontario tailings sites (117). In the second model, a doubled atmospheric concentration of carbon dioxide will cause the natural vegetation zones to change location. The natural vegetation of northern Saskatchewan will change from moist boreal forest to a cool temperature steppe. However, the natural vegetation of the Elliot Lake and Bancroft areas will remain a cool temperate forest (121).

### 6.3.4 General Comments

Such events as changes in solar activity and volcanic eruptions have short-lived effects on climate. But the carbon dioxide greenhouse effect causes a bias in the climate, a net effect, which is growing with time (123). In the end, however, the predicted climatic change may never happen (118).

### 6.3.5 Summary

Although some of the future effects on Canada's climate, of the greenhouse effect, can be predicted, there is no way of telling how these climatic changes will affect Canadian uranium tailings sites. That which can be surmized about the future changes is not specific enough to draw conclusions.

#### 6.4 CONCLUSIONS

- Canadian uranium tailings sites may be glaciated soon enough (within 100 000 years) that radionuclide release will probably occur.
- Drought could strike the tailings impoundments many times within the next 100 000 years. Significant impoundment and tailings erosion may or may not occur.
- There is no way of telling how the carbon dioxide (CO<sub>2</sub>)-caused greenhouse effect will affect the tailings.

## 7. LONGEVITY OF TAILINGS IMPOUNDMENTS IN GENERAL

Engineering design can ensure the integrity of an impoundment for several decades, and can make the risk of impoundment failure in several centuries very small. But for uranium tailings impoundments to succeed in their purpose, failure (i.e. significant tailings and radionuclide release to the environment) cannot occur for at least 100 000 years. The following discussion examines the ability of engineered structures in general, and surface uranium tailings impoundments specifically, to work successfully in the long-term.

Although engineering experience allows a relatively accurate prediction of materials behaviour for up to a few hundred years, it provides a poor estimate of the recurrence intervals of extreme natural events and the response of landforms to these rare events over long periods (6). Similarly with man-made tailings containment systems, even the most soundly engineered system cannot be expected to ensure retention of the bulk solid tailings material in the indefinite future. Due largely to geomorphological and climatological processes which can be expected to occur in the long-term, it can be expected that a containment system will eventually suffer partial or substantial damage, leading to the dispersal of tailings material. The difficulty of being able to predict either quantitatively or qualitatively the nature and extent of all manner of geomorphological and climatological processes in the long-term, i.e. beyond the first few thousand years, makes it difficult to be confident that the release of contaminants will not exceed design performance standards (124).

Two of the world's oldest existing earthworks are in Anharadapura and Pollanawura, Sri Lanka. They are conventional homogeneous earth dams, about two thousands years old. One of them is 26 km long with a maximum height of 30m. They were dug out of the jungle at the turn of the 20th Century. They were found to be in excellent condition and are back in use (125). The dams show that structures such as uranium tailings impoundments may remain intact for at least several thousand years.

A study has concluded the following about the lifetime of uranium tailings impoundments in Canada; impoundments cannot be expected to survive 100 000 years. According to this study before failure and washout, the surface of the tailings will have been slowly and uniformly eroded with total removal over a period as short as 1000 years. This study also concluded that the radionuclide content of this effluent will probably exceed present day standards and guidelines. The failure will in effect extend the area of the original tailings site. Also the hazards of radon gas, gamma radiation, release rates of radionuclides and stable heavy metals are increased (16).



It can be concluded that today's level of waste disposal technology may be used to safely contain uranium tailings in surface impoundments for several thousand years. However, against the threat posed by natural events, it is probably not adequate for containment in the time period of at least 100 000 years necessary for uranium tailings.

## 8. CONCLUSIONS

Flooding caused by heavy precipitation storms, is the natural event that will probably release the greatest amount of radionuclides from Canadian uranium tailings impoundments. It is followed, in order of decreasing amount of release, by wind storms, earthquakes, drought and forest fires. Glaciation cannot be ranked with the other natural events because its occurrence is unpredictable. The carbon dioxide (CO<sub>2</sub>)-caused greenhouse effect cannot be ranked because the consequences at the tailings sites are unknown.

At Lorado, natural events will probably release most of the radionuclides to the environment within several hundred years. At Gunnar, within the same time frame, a large portion of the radionuclides will probably be released to the environment. At Elliot Lake, significant radionuclide release could occur within several hundred years, and severe release in one to two thousand years. At Bancroft, significant radionuclide release by natural events might occur in several hundred years. At Key Lake and Rabbit Lake, significant release will probably not occur for at least several hundred years. At Beaverlodge, significant release should not occur.

Between 10 000 and 100 000 years from now, release of radionuclides by natural events will likely be severe at all the tailings sites. At some, release could be total.

## 9. RECOMMENDATION

The long-term effects of natural events on the tailings impoundments should be re-assessed when all the tailings sites have been finally closed-out and abandoned. At that time, the exact configuration will be known.

## 10. ACKNOWLEDGEMENTS

I thank Mr. G. Marois of TID, CANMET for his help with CANMET's MINPROC and MINTEC databases. Mr. R. Gauthier of the Inland Waters Directorate of Environment Canada also supplied useful references through the WATDOC database.

Special thanks go to: Mr. T. A. Shepherd of Colorado State University for permission to include in this report, a chapter from his Ph.D. dissertation; Mr. L. Welsh of the Canadian Climate Centre, for climate information; Mr. A. Vivyurka of Rio Algom Limited for first-hand accounts of the Elliot Lake tailings sites; Mr. P. Basham of the Earth Physics Branch of EMR, for references of earthquake information and for explanations of seismic phenomena; Mr. D. Murray of Agriculture Canada for descriptions of revegetation on Ontario uranium tailings; Mr. M. Filion of Eldorado Nuclear Limited for information about the Rabbit Lake site, and Mr. W. Tao of Geocon, also for Rabbit Lake information.

I gratefully acknowledge the helpful insight given me by: Mr. C. E. Van Wagner of the Petawawa National Forestry Institute; Mr. B. Conlin of Komex Consultants, Calgary; Mr. J. Drysdale of the Great Lakes Forest Research Centre, Sault Ste. Marie; Mr. M. J. Newark of the Canadian Climate Centre, Toronto; Mr. J. Johnston of the Crowe River Conservation Authority, Marmora; Mr. O. Fleming of the Ontario Ministry of Natural Resources, Bancroft; Mr. M. A. J. Matich of Geocon, Toronto; Dr. N. Davé of CANMET's Elliot Lake Laboratories; Mr. K. Gorham of the Saskatchewan Ministry of Parks and Renewable Resources; Mr. C. Chakravatti of Denison Mines Limited, Elliot Lake, and Mr. L. MacPhie of Geocon, Montreal.

The contribution of the National Uranium Tailings Program staff was much appreciated. The help of Mr. G. Tremblay in assembling this report was especially valuable.

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## APPENDIX A

### LONG-TERM POTENTIAL MODES OF FAILURE

*The material in this appendix is taken directly from Chapter IV of:*

*Shepherd, T. A. (1979). "A methodology for evaluating uranium tailings management alternatives". Ph.D. dissertation. Colorado State University, Fort Collins, Colorado.*

*The author's permission has been obtained to include this material. Where appropriate, some editing has been carried out.*



## LONG-TERM POTENTIAL MODES OF FAILURE

This section describes the various potential modes of failure that could cause the release of radioactive material and radionuclides from a tailings containment facility. The discussion of potential failure modes considers the post-operation, long-term phase of the tailings disposal operation. The investigation carried out in this research as well as that done by Nelson and Shepherd (1978) show that the most significant problems of safe containment of the contained tailings and radioactive material is over the long-term periods of post-operations. The NRC, in their tailings management review process which is part of the mill licensing program, concentrate to a large degree on the long-term aspects of impoundment stability and containment. It is over this long time period that the most serious problems of radioactive release are likely to occur because of conditions that will become evident.

The post-operation phase encompasses a very long time frame which is based upon the long-lived potential hazard of radionuclides contained. The half life of Thorium 230, which is approximately 83,000 years, is used as a general upper limit for long-term consideration but for convenience 100,000 years is used. The entire post-operation period is subdivided into three periods: short long-term which runs from the cessation of operation for several hundred years into the future, the medium long-term which extends several thousand years into the future, and the long long-term which carries the evaluation to approximately 100,000 years after abandonment following the system established by Nelson and Shepherd (1978). This research showed that this division of long-term performance evaluation was useful because the mechanisms that control potential failure change in character over time and these changes are clearly reflected by the subdivisions used.

The description and discussion of the long-term potential modes of failure presented in the following are, with some minor changes, as developed by Nelson and Shepherd (1978) in their investigation on long-term stability and reported in "Evaluation of the Long-Term Stability of Uranium Tailings Disposal Alternatives." It is with their kind permission, and that of their contributors, Wayne A. Charlie and John D. Welsh, that their Chapter IV can be used here.

TABLE A-1. Long-term potential modes of elemental failure.

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Cover:

Differential settlement  
Gullyng  
Water sheet erosion  
Flooding  
Chemical attack  
Shrinkage

Liners:

Differential settlement  
Subsidence of subsoil and rock  
Chemical attack  
Physical penetration

Embankment:

Differential settlement  
Slope failure  
Gullyng  
Water sheet erosion  
Wind erosion  
Flooding  
Weathering and chemical attack

Revegetation:

Fire  
Climatic change

Water diversion structures:

Slope failure  
Obstruction

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## Long-Term Failure

Long-term failure of a tailings impoundment can occur as a result of the long-term behavior or failure of some element of the impoundment; or it may occur as the result of a natural phenomenon that either was not anticipated in the design or that is of a magnitude larger than for which the impoundment was designed. An example of the former would be failure of the cover due to various factors. An example of the latter would be the occurrence of an earthquake of magnitude 8 whereas the impoundment may have only been designed on considerations of an earthquake of magnitude 6.

The likelihood of failure and consequent severity of failure of these two categories of failure would be considered somewhat differently. Consequently, the potential modes of failure to be considered herein have been categorized into elemental failures and failures due to natural phenomena.

The discussion of these potential failure modes in the following section considers also the magnitude of release of radionuclides and the decrease in attenuation of gamma-ray emission rate. Although the release of radionuclides is a different mechanism than the attenuation of gamma-ray emission, the general term "magnitude of release" will be used in subsequent discussion to refer to either one or both mechanisms unless it is necessary at that point to differentiate between them.

## Discussion of Elemental Failures

The list of long-term elemental failure modes considered in this investigation is shown in Table A-1. This list has been compiled on the basis of observations, experience of the investigators, and discussion with personnel from Argonne National Laboratories and the Nuclear Regulatory Commission.

### Cover

The cover on a tailings impoundment is provided primarily for the purpose of reducing radon emanation from the tailings. The cover may consist of a single material such as overburden, topsoil or native soil mixed with an additive such as cement or clay; or it may consist of an initial liner of relatively impermeable material such as clay or asphalt which is then covered with rock or overburden to provide stabilization. Increased release or radioactivity or gamma-ray emission may result from failure of either or both elements. If both a liner and cover exist, the interaction between the two must be taken into account in assessing the severity of a failure.

### Differential Settlement of Underlying Material

Causes and description. If differential settlement of either the foundation material or the tailings occurs, displacements may be induced in the liner that would cause failure. If the foundation soils beneath the impoundment are irregular either in thickness or compressibility the differential settlement may be relatively large and may occur across a short distance. In this case a shear type failure such as shown in Figure A-1 would result and failure would be localized.

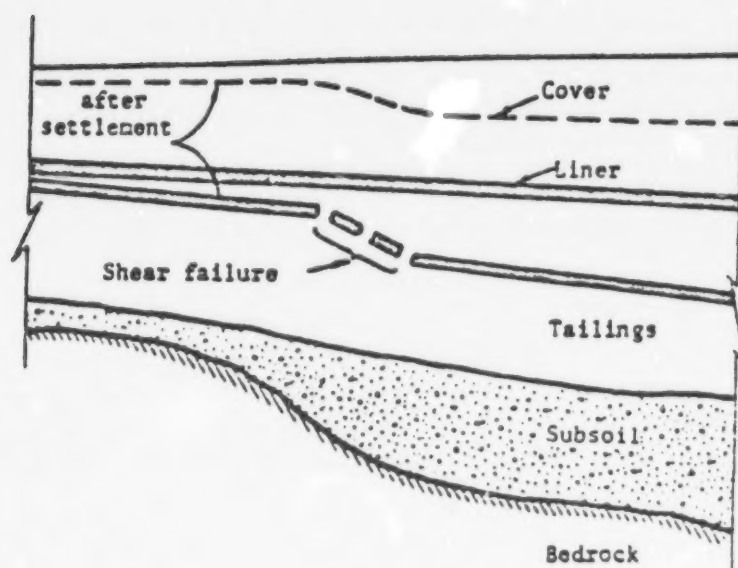
Alternatively, differential settlements may occur across large distances (i.e., several hundred feet). Settlement may be due to compression of both the foundation material and the tailings themselves. Differential settlement across a valley is to be expected because the alluvium and tailings would be deeper near the center of the valley than toward the outer edges.

When settlement is considered in relation to its effect on the cover, compression that has occurred prior to placement of the cover is obviously of little concern. During construction of the impoundment the coarse tailings placed near the embankment would compress almost immediately. Consolidation of that material would, however, be nearly completed before placement of the cover.

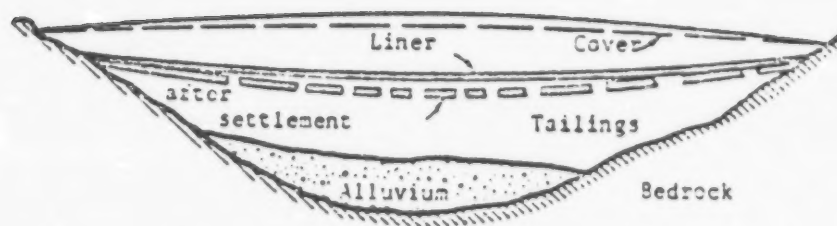
The fine tailings in the slimes zone, however, are much less permeable and would continue to consolidate after placement of the cover. Consequently, differential settlement between the outer edges of the impoundment and the slimes zone would be expected.

Differential settlement due to compression of the tailings and fairly uniform alluvium would occur fairly continuously across the width of the impoundment. The result would be a general cracking of the material due to tensile stresses as shown in Figure A-1b. The degree of cracking would be expected to be greater near the slimes zone because of the larger settlement there. That may be important because the radium concentration in the slimes would be expected to be greater than in the relatively coarser tailings sand (IAEA 1976, Borrowman and Brooks 1975). The resulting radon flux from the slimes may be more than an order of magnitude greater than from the sand (Dames and Moore 1977).

Differential settlement would be a continuously occurring process. The greatest amount of settlement would be expected to be completed within a period of time that could range from only a few years (5 or 10 years) up to 100 or 200 years. In mountain areas the alluvium would be expected to be somewhat permeable ( $10^{-3}$  to  $10^{-4}$  cm/sec.) allowing consolidation to occur fairly rapidly. The time required for the tailings to consolidate will depend on the rate at which pore pressures can dissipate through both the underlying and overlying liners and covers. A period of 100 to 200 years,



(a) Shear Displacement



(b) Tension Failure

FIGURE A-1. Failure of cover due to differential settlement  
(Nelson and Shepherd 1978.)



however, is a relatively long time for consolidation to occur in a natural soil of the general dimensions and permeability to be expected in a tailings impoundment.

Other factors that may contribute to differential settlement would be the existence of collapsing soils or subterranean features that may contribute to localized subsidence. These factors are discussed in more detail with regard to the liner under the tailings.

Differential settlement due to those factors would probably occur rapidly and could occur at any time after abandonment. For example, slowly occurring compression of some foundation soils may increase seepage rates that may in turn introduce more water into an area containing collapsing soils. The collapse of the soils may then cause greater seepage rates that may further increase the differential settlement and area of influence.

Differential movement may also result from upward movement of the foundation soil due to swelling of expansive clays or clayshales. The net effect of the cover due to heave would be similar to that of compression.

Interaction with other failure mechanisms. Failure of the underlying liner could accelerate the rate of consolidation of tailings but would not influence the magnitude of compression of tailings to be expected. If collapsing soils or soluble rocks (e.g., limestone) exist below the tailings, failure of the liner could also contribute to subsidence and differential movement of the cover. Other than those factors it is not expected that other potential failure mechanisms would contribute to differential settlement.

Differential settlement, however, can change the drainage characteristics over the impoundment and may contribute to either water or wind erosion. Also shrinkage cracks may interact with cracks induced by settlement.

Methods of prediction. The amount and rate of differential settlement to be expected can be analyzed on the basis of one-dimensional consolidation theory. Methods of analysis are well known in the field of soil mechanics and are discussed in most textbooks on soil mechanics (e.g., Lambe and Whitman 1969, Terzaghi and Peck 1967, Wy 1976, Sowers and Sowers 1970, etc.).

More sophisticated methods of analysis utilizing two-dimensional consolidation theory and testing methods that duplicate the stress path followed in loading the foundation soils are also discussed in the literature (Lambe 1964, Shiffman et al. 1967).



Secondary consolidation and creep should also be considered in assessing the potential for long-term differential settlement. Secondary consolidation is normally not of great magnitude in sandy soils or soils of low plasticity such as are frequently encountered in mountain alluvium. However, a significant amount of secondary consolidation has been observed in some tailings and has been attributed to the very angular nature of tailings from hard rock ore (Nelson et al. 1977). In areas where the foundation material has a high plasticity such as clay or clayshale, creep may contribute to differential movements over a long period of time (Nelson and Thompson 1977, Crawford 1965).

The amounts of secondary consolidation can be predicted on the basis of laboratory consolidation tests (Lambe and Whitman 1969). Creep measurements, however, require long time periods and the prediction of creep displacements, particularly where shear deformations enter in, require more sophisticated methods of analysis (Nelson and Thompson 1977). Within the present state of the art, however, sophisticated methods of analysis are probably not warranted and it is doubtful that much accuracy could be obtained for prediction of displacements over a period of time much in excess of about 100 or 200 years.

Likelihood. The likelihood of differential settlement occurring is great. However, the likelihood of differential settlements being of a magnitude that will allow the release of radioactivity will be very site specific and will depend to a large extent on the foundation soils and the nature of the tailings. During the design phase of an impoundment, predictions will be made of the amounts of settlement that will occur and the liner will undoubtedly be designed to accommodate relative displacements of the amounts anticipated. Failure would therefore consist of the occurrence of differential settlement of an amount greater than that predicted. The likelihood of failure will be influenced by the factor of safety that is employed in the design, the variability encountered in the foundation soils and tailings, and the confidence level of the analyses employed.

Magnitude of release. The potential magnitude of release due to failure of a cover as a result of differential settlement is very site specific and will be influenced greatly by the interaction between the cover liner and the cover. The magnitude of release will depend on the extent to which cracks can remain open for the entire thickness of the cover. Embankment dams constructed of brittle cohesive material of low plasticity have been observed to be particularly susceptible to cracking and can support cracks several feet deep (Sherard 1973). On the other hand, cohesionless sandy soils will not support open cracks.

Cracks in pavements have been observed to provide little resistance to radon emanation (private communication with H. G. Olson). It may, therefore, be assumed that relative to the tailings or cover material the crack would provide negligible resistance to release of the radon to the atmosphere. Thus, if a crack develops in the cover radon would be released from tailings on either side of the crack for a distance of the magnitude of the relaxation length. Sears (1975) gives a half thickness of sand with a low water content as being about 4 feet for radon. Thus, for purposes of comparison it will be assumed in subsequent discussion that if a crack develops, the release through the crack would be equivalent to the full release of radon from tailings extending to a distance of about 4 feet on either side of the crack. The actual equivalent distance will depend on the grain size and water content of the tailings and may vary somewhat from the assumed value of 4 feet depending on the particular tailings being considered.

The factor governing the release of radon is, therefore, not the width of the cracks but the spacing of cracks. If a shear type displacement occurs (Figure A-1a), the cracks would tend to be concentrated more in that area and the area of release would be the general area of distress plus a distance to each side of about 4 feet.

If the differential settlement is fairly uniformly distributed (Figure A-1b), the cracks would tend to be fairly uniformly spaced. Cracking due only to differential settlement would cause a minimal release of radon. However, cracking caused by shrinkage must be considered together with cracking due to differential settlement and in the case of shrinkage significant release of radon may occur. That will be discussed more fully in a later section.

Site considerations. Site considerations that will influence the differential settlement are primarily the subsurface soil and rock profiles. For an impoundment of relatively low height (approximately 100 feet) the nature of the soil lying over the bedrock will govern the settlement that will occur. For very high impoundments (several hundreds of feet) the compressibility of the bedrock may have to be considered as well. The worst situation would exist where the thickness of the subsoil and the tailings varies greatly across the site. If the subsoil profile is erratic, such as may be caused by old erosion channels in the bedrock, shear displacement of appreciable magnitude could result. Both the variability and the erratic nature of the subsoil must be considered.

If collapsing soils are found to exist in the subsoil, they should be treated as discussed below with regard to design. If water soluble rocks, such as limestone, or if underground cavities, such as in karst topography or from mining, are found to exist, consideration should be given to relocation of the site.

Time dependence. Primary consolidation and hence the greatest differential settlement would be expected to occur within a time period ranging from only a few years (5 or 10 years) up to about 100 or 200 years. In some cases, where large deposits of soft, relatively impermeable foundation materials or where the tailings contain a significant amount of clay (e.g., Florida phosphates) the time required for consolidation may increase to several hundred years.

Secondary consolidation and creep, however, may continue for considerably long periods of time. Examples of this are seen in the Leaning Tower of Pisa that continued to tilt even after several hundred years. A large monument (Chedi) in Nakhorn Pathom, Thailand, is appearing to continue to settle approximately 400 years after its construction. Evidence of movement of a slope over periods close to 1000 years have been observed (Crawford and Eden 1967). Although those examples are somewhat different than tailings impoundments they indicate that deformations due to secondary consolidation and creep may occur for many years.

If deformation is due to creep of the foundation materials and potential shear instability of the foundation materials (e.g., bearing capacity or slope instability) accelerated movements may occur even thousands of years after construction of the impoundment (Crawford and Eden 1967). The design, therefore, should provide for stresses low enough that accelerated creep would not occur (Nelson and Thompson 1977).

In summary, failure due to differential settlement would be expected to be a short-term phenomenon (hundreds of years) with potential for movements to continue close to the medium-term (thousands of years). Over a period of 100,000 years it is expected that the displacements would have either slowed down to the point that they would be of little consequence or else failure would have occurred. More importantly, however, differential settlement is a subsurface phenomenon and the surface phenomena contributing to instability would far outweigh the effect of differential settlement on the long, long-term scale.

### Gullying

Causes and description. The causes of gully formation on the cover of a tailings impoundment would be a combination of steep slopes, the concentration of runoff, and an erosive soil. If gullies were to form, it is possible that relatively large quantities of cover material could be transported. If the gullies are deep enough tailings material could be transported also.

Gullies generally progress in a headward direction as a result of concentrations of runoff in particular areas. They begin at a location of localized erosion, generally at points of abrupt changes in slope. Because gullying is more severe in areas of steep slopes, it is unlikely that significant gullying of the cover would occur independently of serious gullying or instability of the retaining embankments. If gullies form directly on the cover without having been started in the embankment the effects would probably be local. Material eroded from one location in the cover would probably be redeposited within a short distance. Local thinning of the cover would occur, but removal from the impoundment would be unlikely.

The release of radioactivity by gullying in the cover formed by the headward progression of gullies in the embankment is considered at a later point with regard to failure of the embankment.

Interaction with other failure mechanisms. Gullying in the cover may concentrate runoff at particular points in the embankment and cause either major gullying of the embankment or slope instability due to an increase in water content. Minor gully formation on the cover could therefore result in more serious problems in the embankment.

Differential settlement could cause cracks to form in the cover which would act as channels for runoff and result in gully formation if slope and runoff were sufficient. Differential settlement could also result in the formation of general depressions in areas or change the original grading on the cover. That may result in the concentration of runoff or slopes steep enough to initiate gully formation.

Any increase in precipitation, decrease in infiltration capacity of the soil, or loss of vegetation on the cover could initiate gully formation. On the other hand, cementation of the cover material by natural weathering could retard the formation of gullies.

Methods of prediction. No mathematical models are in existence that predict gully formation. Some research regarding gully formation has been done in the Piceance Creek drainage basin in northwestern Colorado (Schumm 1977).

It may be tenuous to attempt to define a relationship between critical slope and drainage area (or runoff) that could be applied to the cover and embankment of a tailings impoundment. However, observation of gullying in adjacent landscapes may assist in predictions if similar soils are used for the cover. Care must be exercised in extrapolating from a natural situation to the impoundment because of differences between natural soils and the cover. Potential differences in vegetative cover will also influence gullying. The concept that a critical threshold may exist between a stable and unstable situation is well worth exploring and is an area that deserves further research.

Likelihood. The likelihood of gully formation in the cover of an impoundment other than due to headward progression of embankment gullies will generally be low. The likelihood of gullies progressing from the embankment is considered in a later section regarding embankments.

The low value for likelihood of failure is based on the following assumptions:

1. The slopes of the cover are gentle.
2. The cover was graded during construction to minimize the concentration of runoff.
3. The drainage area of the impoundment is isolated by diversion structures from regional drainages.
4. The cover is protected by either vegetation or some erosion resistant material.

If these assumptions are not valid for a particular case the likelihood of failure would increase. The amount by which it may increase would be site specific.

Magnitude of release. The potential magnitude of release due to gulying on the cover would be a function of the amount of cover material and tailings removed. The mode of release would most likely be an increase in radon emanation due to a reduction in cover thickness in certain areas. Severe gulying to depths greater than the cover thickness could result in erosion of the tailings as well. The latter would be an extreme case which would probably be caused only by the unlikely existence of steep cover slopes or the progression of embankment gullies into the tailings.

Discontinuous gullies could be formed that would erode cover material from one location and deposit it at another, still within the impoundment. The increase in the release of radon gas to the atmosphere would be a function of amount of cover removed and the extent of the gulying.

The magnitude of release would be site specific and would increase with slope and local drainage area on the cover. The procedures used to estimate magnitude of release for cracking of the cover due to differential settlement could be employed to quantify the magnitude of release for a particular site.



Site considerations. The site considerations that will influence the likelihood of gully formation on the cover is primarily precipitation. The annual amount, frequency, intensity, and duration are the factors of primary influence. High intensity, infrequent storms such as are common in arid or semi-arid regions do not support vegetation and are likely to produce the kind of runoff that would result in gully formation. Topographic location would be important if the impoundment is not isolated from the local drainage basin by diversion structures. In that case, drainage patterns, drainage area, and location of the impoundment within the drainage area become important.

Design consideration. Important design considerations to prevent gully formation are:

1. Avoidance of long steep slopes.
2. Grading of the surface to avoid concentration of runoff, or to divert runoff into areas that can be stabilized against gulying.
3. Establishment of vegetation cover or placement of erosion resistant cover such as rocks.
4. Avoidance of highly erodible soils on the surface.
5. Maintenance of soil infiltration capacity as high as practicable.
6. Diversion of external runoff from the impoundment.

Observation of gulying in the local natural landscape can provide information on gully potential and design requirements.

Time dependence. The potential for the formation of gullies on the impoundment cover is time dependent in the sense that the likelihood of gully formation increases for longer time periods. If environmental and geomorphological conditions do not change and if the cover has been constructed in a manner to remain stable it would be safe to assume that gulying will not be a problem. However, over medium long-term time, and even within short intervals, it is unrealistic to expect conditions not to change.

The climate is likely to change over long periods. Drought may occur for several years followed by years of abnormally high precipitation. A change in precipitation and temperature will affect sediment yield and rainsplash erosion (Schumm 1977, Mabutt 1977). Figure A-2 demonstrates the relationship between climate and sediment yield. Figure A-3 shows the effect of temperature on the relationship between mean annual runoff and mean annual precipitation. These data clearly demonstrate that the erosional process will change with changing climatic conditions, and the potential for initiating increased gulying will be a function of the environment before change and the direction of change.



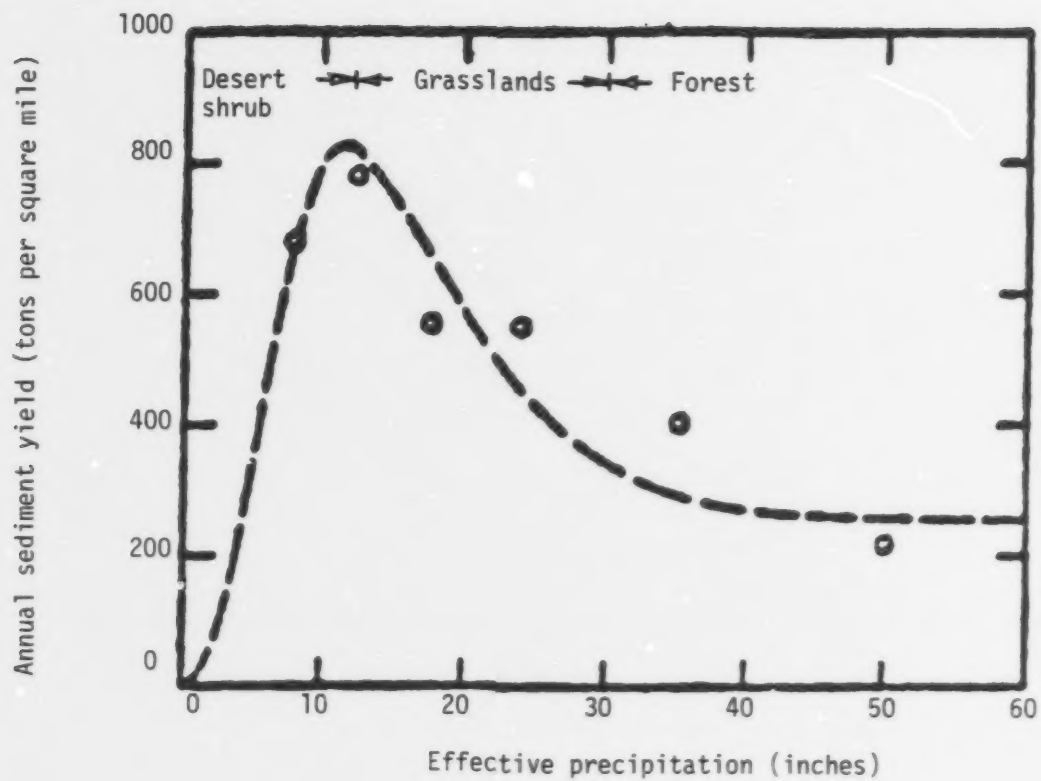


FIGURE A-2. Variation of sediment yield with climate as based on data from small watersheds in the United States. (From Schumm 1977.)

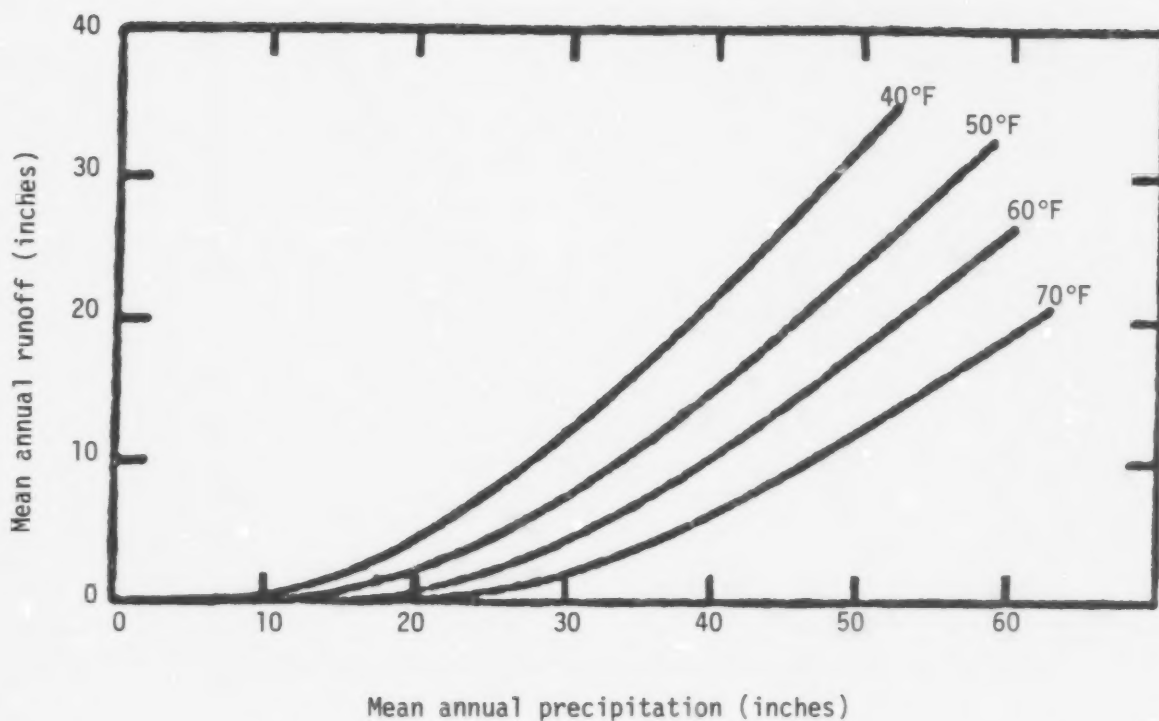


FIGURE A-3. The effect of average temperature on the relation between mean annual runoff and mean annual precipitation. (From Schumm 1977.)

Major climatic changes may not occur within the short long-term period, but could certainly be expected within a medium long-term period. For example, changes in climate and a consequential decrease in suitability of the area for agriculture has been advanced as an explanation for the desertion of the Mesa Verde area about 1000 years ago.

Another important consideration is that gully formation as well as other erosional processes may not be continuous, but episodic in nature. Schumm (1977) discusses this in relation to thresholds and responses of the system to continuous processes such as denudation.

Over long periods of time being considered herein, regional effects become more important in predicting the changes likely on the site. The scenario developed for future climates and the specific location of the impoundment become the most important factors in predicting future responses of the cover to gullying.

#### Water Sheet Erosion

Causes and description. Water erosion on the cover of a tailings impoundment will be caused by either raindrops striking the surface or water flowing over the surface. The combination of these two phenomena can detach and transport significant quantities of soil from an area. The slope of the land, the nature of the soil, the duration and intensity of the rain, and the ground cover are among the most important factors influencing the amount of erosion that will occur (Stallings 1953).

Soil may be transported off the area or it may be dislodged from one part of the cover to be redeposited in an adjacent, lower location. Over a period of time large quantities of material could be removed from the surface reducing the cover thickness of in the extreme case removing the cover entirely. If erosion is extensive, tailings material might be exposed and removed. Erosion of that extent, however, would require erosion of the embankment or confining structure as well.

Soil and drainage characteristics of the surrounding area may be important in evaluating total erosion potential of the site. The total drainage area above the impoundment may supply surface runoff to the site or it could introduce sediments to the impoundment if the location provides a depositional environment.

Interaction with other failure mechanisms. Surface erosion will be affected by runoff from the surrounding area if it is allowed to reach the cover. Therefore, the operation of diversion structures has an important influence on erosion. In this regard, off-site erosion can affect the operation of diversion structures by supplying silt which may clog them. Also, long-term changes in drainage patterns in the surrounding area may introduce additional runoff to the site.

Settlement within the impoundment can change surface characteristics resulting in changes in the erosion potential. Climatic change will affect erosion if changes in precipitation occur. These effects may be manifested in terms of both vegetation response and amount of runoff.

Likelihood. The likelihood that water erosion will occur is almost a certainty. The amount of soil loss will vary depending upon the particular site, soil conditions and nature of the cover.

It is conceivable that deposition rather than erosion could occur. This is a specific site condition and cannot be assumed without analysis. Erosion is the most likely expectation, especially if the cover is graded to eliminate impoundment of water.

Magnitude of release. The potential release of radioactivity will be a function of the amount of erosion that occurs and the reduction of cover thickness. The principal radiation release for erosional process failures of the cover will be radon gas emanation. The effectiveness of a cover to reduce radon diffusion is a function of the thickness of the cover, the radon content of the tailings, the water content of the cover soil, and the type of soil used (Sears et al. 1975).

The attenuation of radon emanation as a result of covering to various thicknesses is shown in Figure A-4. Also shown is the effect of moisture content and soil characteristics on attenuation.

For all failure mechanisms that result in a reduction of cover or cover thickness the magnitude of release will be related to a percentage change in release due to loss of thickness.

Extreme erosion could result in the removal of the entire cover. Erosion that extreme, however, would need to be accompanied by erosion of the embankment as well to maintain a slope on the surface.

The magnitude of release from the cover due to erosion would be expected to increase with time. In order to estimate the potential magnitude of soil loss over long time periods it would be necessary to develop future scenarios including climate and management practices.

Site considerations. The site considerations that will influence the potential for erosion are the climate and precipitation, the topographic location with respect to other drainages, and the local vegetation which would be expected to become established on the impoundment.

The local natural vegetation is important to consider because it reflects the nature of the vegetative cover that will ultimately exist on the site. Long-term erosion estimates must consider the evolution of vegetation and soil properties, unless significant commitments to maintenance are to be part of the disposal plan.

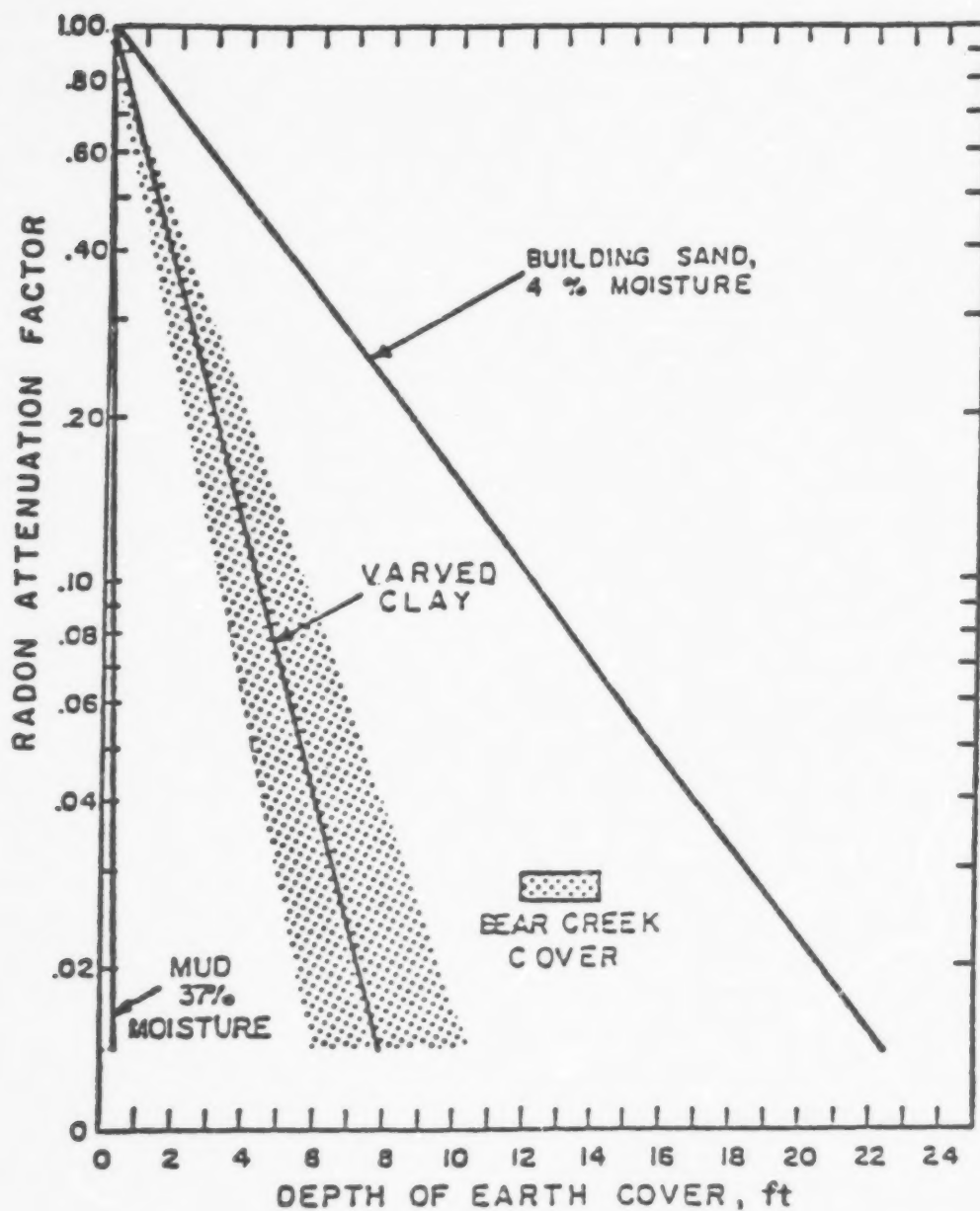


FIGURE A-4. Radon attenuation by earth cover over tailings piles.  
(From Sears et al. 1975.)



Topographic location is important in two respects. First, it must be determined if runoff from areas outside of the impoundment will supply water and, therefore, increase the erosion potential of the site. Secondly, consideration must be given to the potential for deposition of sediments on the impoundment from outside. If the impoundment can be located such that natural erosion of the surrounding area would deposit material on the cover, particular benefits in the form of eventual burial could be realized.

Time dependence. Erosion is a continuing process and will continue and change as conditions change over time. It is impossible to predict increases or decreases over time without also describing the hydrologic changes that can be expected. As the time period under consideration becomes long, the natural erosional processes in the specific locales may provide the best clue to future potential erosional patterns.

In general, erosion will increase continuously with time unless natural processes such as armoring decrease the erosional rate. Prediction of soil loss may be possible up to the medium long-term period. However, for long long-term considerations it is nearly impossible to predict what changes in erosion might take place.

#### Wind erosion

Causes and description. The three basic ingredients contributing to wind erosion are (Chepil 1956):

1. Loose, finely divided, dry soil.
2. A smooth, bare soil surface.
3. Strong wind.

Soil particles may move as suspended dust and be carried great distances or they may move relatively short distances by saltation or surface creep depending on size, surface condition and wind velocities (Chepil 1958, Woodruff et al. 1972).

Wind erosion can remove significant quantities of topsoil from a site. The effects of wind erosion can be the destruction of vegetation by abrasion, the accumulation of soil in culverts and diversion structures, and the removal of the productive fine grained silts and organic constituents of a soil.

Wind erosion can also take the form of blowouts in tailings embankments, similar to those common in beach dunes. These blowouts can continue to grow, thereby reducing stability and resulting in extensive movement of the tailings embankments. If left unchecked, wind erosion could cause movement of fine grained tailings material over great distances.

Interaction with other failure mechanisms. An important interaction with other failure mechanisms is the potential effect wind erosion could have on diversion structures. Diversion ditches can become filled with coarse soil fractions moved by surface creep and saltation. With diversion structures clogged, surface runoff that is intended to be diverted away from the impoundment may flow over the surface of the cover. Another important effect of wind erosion may be the potential loss of protective vegetation due to loss of soil fertility or destruction by abrasion of wind blown particles. The loss of vegetation by fire, drought or pestilence will increase the potential for wind erosion.

Methods of prediction. Wind erosion can be estimated by using a soil loss equation similar to the USLE. This equation was developed by W. S. Chepil and is described in several reports (UWRL 1976, Woodruff and Siddoway 1965, Woodruff et al. 1972).

The wind erosion equation is:

$$E = f(ICKVL)$$

where: E = soil loss by wind in tons/acre/year  
 I = soil wind erodibility factor, related to the soil fraction greater than 0.84 mm as shown in Table 12.  
 I<sub>s</sub> = soil wind erodibility index, needed to compute erodibility for windward slopes, Figure 15. For slopes, erodibility becomes I' = I x I<sub>s</sub> in tons/acre/year.  
 C = climatic factor  
 K = soil surface roughness  
 V = equivalent quantity of vegetative cover  
 L = unshielded field width measured along the direction of the prevailing wind.

These variables, established by using local soil or climatic data, or published data as presented in the Utah Water Resource Laboratory handbook (UWRL 1976) for example, are then manipulated to estimate total potential soil loss by use of a graphical solution.

The equation is a useful management tool for determination of potential wind erosion under existing conditions, and for determination of surface conditions and sheltering necessary to reduce wind erosion to a tolerable amount (Woodruff et al. 1972). The equation serves as a guide for determining the management conditions necessary to control wind erosion under conditions at a given site (Heil 1977).

It is important to note that the computed soil loss is an estimate based upon specific site and management conditions. It can be valuable in showing the relative effectiveness of alternatives for wind erosion control. It is the best tool available for prediction of wind erosion losses and does define the factors that need to be considered when evaluating wind erosion potential. Its ability to predict long-term wind erosion losses, however, is limited by changes which the input factors may undergo over time.

Likelihood. The likelihood that wind erosion will occur is high. The amount of soil material moved and the distance of movement is a function of the factors considered in the wind erosion equation.

Magnitude of release. The magnitude of release due to wind erosion of the cover will be a function of the reduction of cover thickness caused by soil loss. The expected mode of release would be increased radon emanation as described in water erosion of the cover.

If no cover exists, or if it is removed by other mechanisms, direct blowing of tailings material is possible. The fine grained portion of the tailings (slimes) would have the highest potential for long distance transport, while the coarser sands would move shorter distances by saltation or surface creep. Long-term exposure of tailings to wind erosion could disperse the radioactive particles over large areas.

Site characteristics. Site conditions that are important factors in determining the wind erosion potential are the soil chosen for the cover, wind speed and direction, precipitation as it affects soil moisture and the nature of the vegetative cover that can be supported. The topographic location of the impoundment with respect to prevailing winds and the unsheltered length exposed to winds also are important to the effective control of soil loss by wind.

Long, open windward reaches will increase wind erosion. Any barrier on the windward side of the impoundment can be effective in reducing wind erosion. As with water erosion, it may be possible to locate impoundments to take advantage of deposition of wind transported soils. Studies of existing wind deposited material can provide guidance in this regard. Location of impoundments at the top of unprotected knolls or ridges, in valleys that channel prevailing winds or diurnal winds, or in areas susceptible to high seasonal winds, such as the Colorado Front Range area, may increase the wind erosion potential.

Design considerations. The design considerations that are important for prediction of wind erosion potential are soil cover characteristics, the soil roughness, the slope of the surfaces, the unsheltered length, and the vegetation cover.

Wide, unsheltered and smooth surfaces perpendicular to the prevailing wind enhance the erosion potential. Any barrier that can be placed to break up the flow of wind can be beneficial in reducing the wind erosion potential.

An important factor of design is vegetation. Good vegetative cover is an effective way to control wind erosion. The natural vegetation in the immediate vicinity will suggest what kind of cover can be expected. Grading or diversion to direct precipitation runoff over the cover without enhancing the potential for water erosion or stability problems may be a useful design feature. Changing climates that may affect both vegetation and wind must be considered in scenarios of future wind erosion potential.

Perhaps the factor over which the most control can be applied is the choice of covering soil. Figure A-5 (Chepil 1958) indicates that soil particles having an equivalent diameter of 0.1 mm are most erodible. Chepil (1965) also points out that erodible soil particles can be protected from wind erosion by being sheltered by larger non-erodible soil particles. This protection occurs when non-erodible material projects above the surface in sufficient density to completely shelter the erodible fraction from the wind. This constitutes the phenomenon of armoring described previously.

In many cases the non-erodible fractions are subject to abrasion and disintegration by the bombardment of the moving particles. In such a case the process of protecting projections never is completed and erosion continues. However, if pebble or rock can be incorporated in the soil matrix used for the cover, wind erosion potential could be reduced by the formation of a protective, non-erodible pavement.

Monitoring, maintenance and remedial measures. Monitoring techniques similar to those discussed in water erosion could potentially be employed to observe wind erosion. Most useful are perhaps techniques that would identify changes in vegetation, both on and off the site.

Maintenance and remedial measures, likewise, are of the same nature as for water erosion. One difference would be that with wind dispersed materials, capture and cleanup may not be possible. Timely maintenance and identification of design deficiencies or problems related to changes in climatic conditions and subsequent correction are important to long-term wind erosion control.

Time dependency. Wind erosion is possible throughout the entire time interval. Changing conditions or the occurrence of interacting failure modes can alter predictions about wind erosion potential.

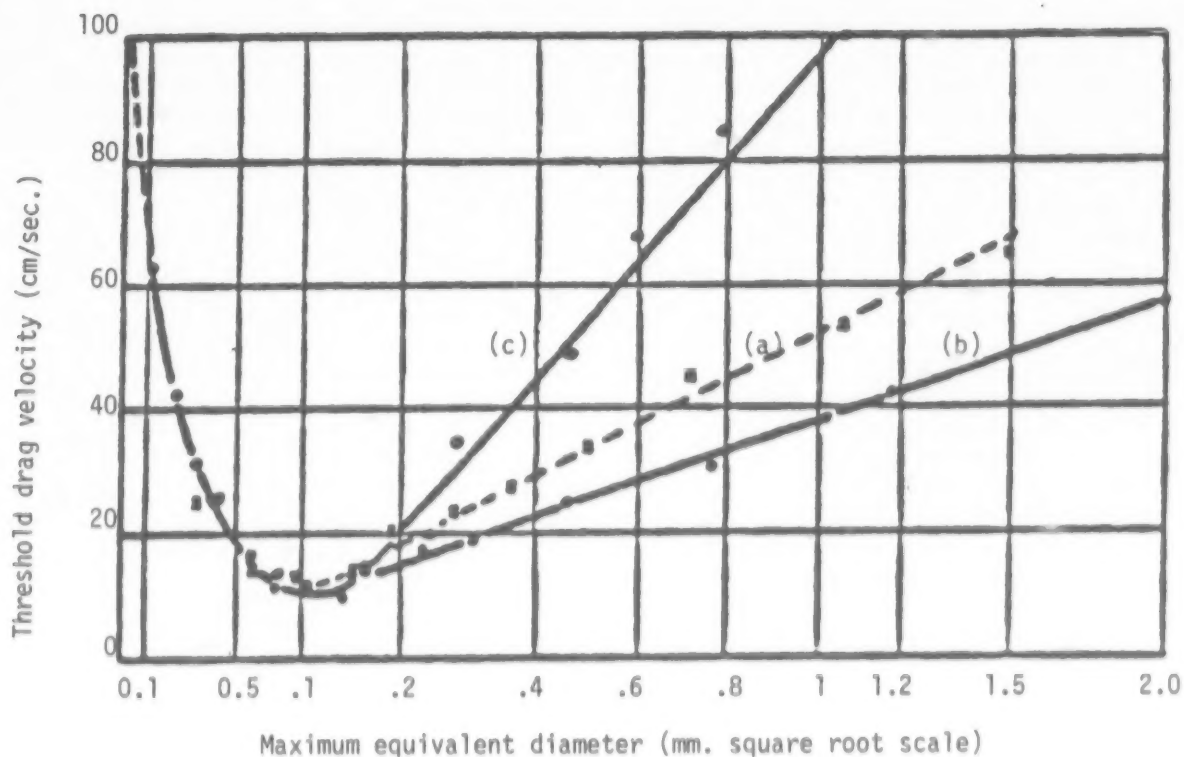


FIGURE A-5. Relation of the threshold drag velocity of the wind to the maximum equivalent diameter of the transported soil particles; a, sieved fractions in which the ratio of minimum to maximum diameter varies as  $1:\sqrt{s}$ ; b, sieved fractions in which the size of particles ranges from fine dust to the indicated maximum size; c, soil containing 15% of the nonerodible clods ranging up to 25 mm in diameter. (From Chepil 1958, p. 7.)



Wind erosion may be expected to occur continuously. If armoring forms pavements on the surface, however, wind erosion can be checked for several thousand years.

### Flooding

Cause and description. Damage to the cover by flooding may result from either the routing of flood waters around or on the impoundment or directly from the precipitation on the cover. If flooding is due to extremely heavy precipitation in the immediate area of the impoundment, sheet erosion and gulying of the cover can result. This event would be a sudden occurrence that would accentuate gulying and sheet erosion as was discussed previously. The effects of those phenomena would then accelerate from that point on.

On the other hand, heavy flooding in the immediate area of the impoundment could result in a washout of portions of the cover. In that case, failure would be in combination with failure of other elements of the impoundment. The general nature of impoundment failure due to a major flood in the immediate area is discussed below, with regard to natural phenomena.

It should be noted that flooding is not necessarily the result of precipitation in the immediate area, but may result from heavy precipitation at any point within the watershed upstream from the impoundment area. The occurrence of major floods is discussed more fully at a later point.

Interaction with other failure mechanisms. Whereas other failure mechanisms would not influence the occurrence of a flood, the effects of a flood will depend to a large extent on the degree of failure that has already occurred on the impoundment due to other modes of failure. For example, gulying, sheet erosion and differential settlement may have altered the surface of the cover such as to cause water to be channeled into a particular area. Also, if differential settlement occurs of sufficient magnitude to cause water to be impounded somewhere on the surface, flooding could result in overtopping and severe erosion of the embankment and cover.

In order to assess the full extent of damage that may result from a major flood (i.e., a flood larger than the design flood) the effects that other factors may have had on routing flood waters over the surface of the cover must also be considered.

Methods of analysis. The prediction of occurrence of a flood of magnitude greater than the design flood is discussed at a later point with regard to natural phenomena. The extent of damage that may occur to the cover may be analyzed on the basis of models of gulying and erosion as discussed in other sections of this report.



Likelihood of occurrence. Reclamation and abandonment plans would undoubtedly attempt to incorporate some design features that would minimize damage due to an event of the design magnitude. Thus, failure of the cover due to flooding would generally be coupled with failure of some other element of the impoundment, such as the diversion structures, or else would be the result of the occurrence of an event of magnitude greater than the design magnitude. The probability of occurrence of an event of magnitude greater than the design magnitude within the long time frames being considered herein is relatively high.

The likelihood of damage to a cover due to flooding would also depend greatly on its location relative to the surrounding topography and whether the flooding is accompanied by heavy precipitation at the site. Severe flooding must be expected. Therefore, the likelihood of failure will depend on whether or not the flood water can come into contact with the cover.

Magnitude of release. The magnitude of release resulting from flood damage to the cover will depend upon the amount of cover that may be eroded. It will depend on the location of the impoundment relative to the surrounding topography and the effect that heavy precipitation can have on erosion of the material.

Flood water of depths of several feet are capable of removing soil of a considerable thickness over a relatively short time (Simons et al. 1977). Thus, if major flood waters can come in contact with the cover, it may be expected that the entire depth of cover could be removed in the area of contact.

The magnitude of release would, therefore, be in proportion to the cover area that may come into contact with flood waters. The magnitude of release that may result from erosion due to the largest precipitation event conceivably would be a function of the amount of cover that is removed either by sheet erosion or gullyng.

Site considerations. Within the medium long-term or long long-term periods the likelihood of a flood of major proportions occurring is relatively high. This is discussed in more detail later. It would be undesirable, therefore, to place the impoundment in a natural drainage area unless the upstream catchment area is small. For example, at Bear Creek, Wyoming, although the impoundment is being placed in a natural draw, it is located at the head of the draw very near to the divide between watersheds. Thus, the catchment area that can contribute to flooding is very small.

Design considerations. The most effective design considerations to minimize flood damage are either to select the site such that it does not exist in a flood susceptible area or to utilize natural or man-made flood control structures that will divert flood waters away from the cover. Neither of these measures, however, will be effective against abnormally high precipitation falling over prolonged periods of time directly onto the cover. To design for that situation an erosion resistant cover consisting of either vegetation or material of sufficient grain size or erosion resistance would be applicable. In this regard, it may be desirable to introduce drainage features onto the cover that would direct runoff toward areas in which erosion protection could be accentuated. For example, the cover may be graded toward natural depressions that would be filled with coarse rock material. The more gentle slopes leading into the controlled drainage areas could be covered with vegetation or granular cover to minimize wind and water erosion.

Time dependence. Although the likelihood of occurrence of a flood greater than the design flood is small at any particular time, the likelihood of occurrence will increase in proportion to the length of time period being considered. However, the probability of occurrence would be the same for short, medium or long long-term periods unless climatic changes should occur.

#### Chemical Attack

Causes and description. No cover will be completely immune from chemical attack or weathering. Chemicals, sun, ozone, wind, drying, rain, moisture, heat and freeze-thaw cycle will act on the cover. Usually, guarantees on synthetic liner materials do not cover malfunctions due to chemical attack. Both acid and alkaline leach processes are employed in the concentration of uranium. Therefore, the extraction process will define the general chemical environment of the pond.

Sun, aging and heat appear to be the worse enemies of polyvinyl chloride and polyethylene. Asphalt concrete is also affected by heat because the heat slowly distills the volatile components of the asphalt. Freezing weather and freeze-thaw cycles influence mostly the rigid linings; concrete, shotcrete (Gunite) and asphalt concrete.

Acids attack Portland cement concrete, as do sulfates. Acids and sulfates react chemically with the hydrated lime and hydrated calcium aluminate in the cement. The sulfates of sodium, potassium and magnesium are commonly present in alkali soils and groundwater found in arid and semi-arid regions (Troxell et al. 1968). ACI (1966) discussed chemical effects on various materials, including unprotected concrete.

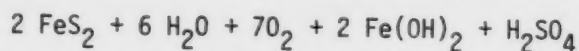
Chemical attack of a soil cover may take place. Throughout geologic time rock and soil masses have been acted on by chemical and mechanical processes. Crystal size and structure of soil and rock are important to the resistance of different minerals to weathering. The

most commonly found minerals in soils are quartz and feldspars. Quartz is relatively stable, but feldspars can change to clay minerals within the short long-term period. Quartz is subject to weathering in an alkali environment. Clay minerals, in turn, can go into solution or weather further in an alkali or acid environment. The end product will depend on the nature of the environment. Examples of chemical weathering are given below.

Hydrolysis. -- Of the chemical processes, hydrolysis is probably the most important. Hydrolysis is the reaction between  $H^+$  and  $OH^-$  of the water and the ions of the mineral. Due to the small size of the  $H^+$  ion, it is able to replace existing cations. The pH is very important in this process because it influences the amount of  $H^+$  ions present. Also, the solubility of many minerals is a function of pH. Mitchell (1976) gives the solubility of alumina and amorphous silica as a function of pH. An example of this type of weathering is the decomposition of feldspar minerals to form the clay mineral kaolinite.

Hydrolysis of a silicate mineral occurs when the hydrogenated surface layers become unstable and break off (Reiche 1945). For the reaction to continue,  $H^+$  ions must be introduced and removal of the soluble products by leaching or precipitation must occur.

Oxidation and reduction. -- An example of oxidation is given by the reaction of pyrite with water to form acid (Keller 1957).



Solution by carbonation. -- Carbonation is the reaction of carbonate or bicarbonate ions with a mineral. Typically, atmospheric  $CO_2$  is the source of carbonate. Carbonation is particularly detrimental to limestone.

Ion exchange. -- If an ion exchange reaction takes place in a clay cover or liner, the soil properties may change. In general, the physical properties of clays, such as plasticity, shrinkage, swelling, strength and permeability are modified by changes in exchangeable cations. The greater the ion exchange capacity of a clay, the larger the potential for property changes (Mitchell 1976).

Chemical weathering products. -- The rate of chemical weathering is dependent on time, temperature, moisture, pH and soil type. During weathering minerals tend to become more stable (Grim 1968). Under conditions of active leaching, acidity favors the concentration of silica and the removal of iron and aluminum. Neutral or alkaline conditions favor the concentration of iron and aluminum (Grim 1968).

Youthful soils have, by definition, little material that has chemically weathered to clays. The intermediate weathering stage of soils introduces some material chemically weathered to illite and/or montmorillonite clays. The advanced weathering stages of soils contain kaolinite as the representative clay mineral (Mitchell 1976).

A drastic change in the environment may cause chemical weathering or reversal of the weathering cycle. For example, illite was formed in a period of less than a year as a consequence of adding potash fertilizer to a soil containing kaolinite (Wood 1941, Grim 1968). Under long-term exposure to acid conditions, the clay minerals in the cover will ultimately be broken down.

Interaction with other failure mechanisms. It is doubtful that other potential failure mechanisms would contribute to chemical attack of the cover. Chemical attack on the cover could change its physical properties possibly leading to failure by shrinkage, changes in permeability, strength, erosion resistance or compressibility. Weathering to soils to a higher clay content could be beneficial in terms of radon emanation (Figure 14).

Methods of prediction. The amount and rate of chemical attack of the cover will be dependent on the type of cover, the possibility of the water in the tailings impoundment interacting with the cover, the pH of the liquid, temperature, degree of weathering and the environment in which the soil existed prior to being used as a cover. Methods of analysis of chemical weathering are discussed in Grim (1968) and Mitchell (1976). Types of materials present in a clay cover that would be most subject to chemical weathering can be predicted based on past experience and/or laboratory tests. Within the present state-of-the-art the accuracy of short- or long-term predictions of the amount of chemical attack on a cover is doubtful. At best it could indicate general trends.

Likelihood. The likelihood of chemical attack on a cover is high. However, the likelihood of chemical attack being of a magnitude that would lead to failure and allow the release of radioactivity is probably small. The likelihood of failure would be site specific and will depend on the type and thickness of the cover, the nature of the tailings and the acidity or alkalinity of the tailings water. Some materials may be very subject to chemical attack under conditions that can exist in a uranium tailings impoundment.

Magnitude of release. The potential magnitude of release due to failure of a cover will be influenced greatly by the nature of the chemical change that may occur. However, as noted above, the potential magnitude of release is expected to be low.

Since repair to the cover would not be difficult to accomplish, the negative utility factor of a failure of the cover would not be very high.



Site considerations. The considerations that will influence chemical attack on the cover are primarily the soil types available for use as a cover, the climate and the process used to leach the uranium.

Design considerations. If chemical weathering of the cover is a problem, recommendations can be made in the design to neutralize the tailings, to use a thicker cover or import material more capable of withstanding the chemical attack.

Time dependence. The time required for chemical attack of materials varies. The rate of chemical change would increase as the thickness decreases, as the permeability increases, in warmer climates, and as the acidity or alkalinity increases. The type of cover, whether it is a synthetic or soil material, and the mineralogical composition of the soil, will influence change. Some change may occur within the short long-term period. After several thousand years it would be expected that no further change would occur.

### Shrinkage

Causes and description. In arid and semi-arid regions desiccation of the cover is almost certain to occur. If cohesive soils are used for the cover, shrinkage may be expected to accompany desiccation. Shrinkage is not expected to be of concern if sandy soils are used for the cover. However, because of the lower permeability, the tendency would be for clayey soils to be used.

Shrinkage results in clays due to a reduction in the bound water and the development of high attractive forces between soil particles during drying. In general, the more plastic clays exhibit a greater potential for shrinking and swelling than do less plastic clays (Holtz and Gibbs 1956, Altmeyer 1956, Seed et al. 1962). If shrinkage occurs, cracks can form in the cover and radon can be released.

A clay cover would probably be placed at a water content close to the plastic limit of the clay. The shrinkage limit is defined as the water content below which further drying would produce no further shrinkage. The amount of shrinkage that may be expected to occur would depend, therefore, on the difference between the plastic limit and the shrinkage limit. For montmorillonite and illite clays this difference may be as great as about 30% or 40% (Lambe and Whitman 1969). Many of the natural clays in the western United States contain significant amounts of montmorillonite.

Interaction with other failure mechanisms. Shrinkage cracks can influence the drainage characteristics over the impoundment and may contribute to either water or wind erosion. If water flows along cracks it may lead to the development of gullies.



Method of prediction. The amount of shrinkage can be analyzed using methods outlined in soil mechanics textbooks. However, it has been shown that the amount of total shrinkage will depend mainly upon the proportion of the clay, type of minerals, exchangeable cations, orientation of clay particles and the degree of aggregation (DeJong and Warkentin 1965), and the initial moisture content.

A greater degree of shrinkage would be expected for clays having relatively high plasticity. In semi-arid regions such as west Texas desiccation of clays in the dry seasons proceeds to a depth as great as 20 feet. Within this depth the clay is broken up by shrinkage cracks (Terzaghi and Peck 1967). In India natural deposits of black cotton soils are characterized by a general pattern of cracks, especially during the dry season (Singh 1967). Cracks about 10 cm wide and over 1 m deep are not uncommon and in deep deposits the cracks may extend to about 3 m.

The degree of shrinkage to be expected can be predicted on the basis of the linear shrinkage of a sample of representative soil.

Likelihood of failure. The likelihood of shrinkage depends primarily on the clay content of the cover material, the moisture content and the aridity of the regions. Wide and deep cracks would be likely to occur in arid zones, but not in humid zones. The amount of shrinkage will be governed by the percentage of clay and the plasticity.

Magnitude of release. The potential magnitude of release due to shrinkage cracks of the cover will be influenced by the spacing of cracks as discussed previously with regard to cracking due to differential settlement. If more than about 2% shrinkage occurs the maximum release of radon will occur. This magnitude of shrinkage is very possible for most cohesive soils. If cohesionless sands are used as the cover shrinkage is obviously of little concern.

Site considerations. Site considerations that will influence the shrinkage will be the aridity of the zone and the nature of material available to be used for the cover.

Time dependence. If desiccation will cause shrinkage cracks it is expected that they would form within the first 100 years after abandonment. The exception for that would be if climatic changes should cause a change from a more humid environment to an arid one.

#### Liners

The liner of a tailings impoundment is provided for the purpose of reducing and controlling seepage from the tailings impoundment. Failure of the liner can be defined as any change in the

liner's behavior or properties that allow seepage rates and possible radionuclide movement at rates faster than the design limits. To predict the severity of failure of a lining, the interaction between the tailings, the liner, the soil below the liner, underdrains and water pressure must be taken into account.

Linings may be classified as natural or man-made, flexible or rigid, impervious or semi-impervious, continuous or non-continuous. Compacted earth liners reduce and control seepage rates, but are not impermeable. Manufacturing defects, seepage at seams, mechanical damage, settlement of subgrade, and aging all contribute to some degree of leakage. Consequently, both compacted soil and man-made linings should generally be backed up with some type of well designed underdrain system. If there is a lining, it probably will leak.

Linings have been used for thousands of years. One of the earliest known applications occurred over 3000 years ago for the Tigris River embankment of Assur where layers of bitumen and clay were used (Asphalt Institute 1965). The rapid growth of linings in the last few years has started a new technology dealing with methods and materials to control movement of water. Table A-2 shows how common linings are classified. Linings of compacted clays are in widest use to reduce and control seepage because of their low cost, flexible nature and longest record of successful performance (Kays 1977).

#### Differential Settlement

Causes and description. Potential failure of the liner due to differential settlement would be similar to potential failure of the cover. However, the settlement of concern with regard to the liner is only that contributed by compression of the subsoil foundation materials. The foundation soils may be expected to be less uniform than the tailings, both in material properties and in thickness. Also, strains within the tailings would distribute the displacement at the surface of the tailings, making the differential settlement somewhat more uniform in the cover. Consequently, there would be a greater likelihood for a shear displacement type of failure in the liner than in the cover (Figure A-1).

One particular concern in some areas may be that problems due to collapsing soils may be accentuated if the liner fails. Thus, whereas differential settlement would usually be a continuously occurring process, sudden differential settlement may result if collapsing soils are present. The sudden differential settlement may occur at almost any time after abandonment or during construction.

TABLE A-2. Lining classifications.

| Flexible                                                    | Rigid                                                                                                                                      | Miscellaneous                                                                   |
|-------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------|
| Plastics<br>Elastomers<br>Asphalt panels<br>Compacted soils | Gunit<br>Concrete<br>Steel<br>Asphalt concrete<br>Soil cement                                                                              | Bentonite clays<br>Chemical treatments<br>Waterborne treatments<br>Combinations |
| Impervious                                                  | Semi-impervious                                                                                                                            |                                                                                 |
| Plastics<br>Elastomers<br>Asphalt panels<br>Steel           | Compacted soils<br>Gunit<br>Concrete<br>Asphalt concrete<br>Soil cement<br>Bentonite clays<br>Chemical treatments<br>Waterborne treatments |                                                                                 |
| Continuous                                                  | Noncontinuous                                                                                                                              |                                                                                 |
| Plastics<br>Elastomers<br>Asphalt panels<br>Steel           | Compacted soils<br>Gunit<br>Concrete<br>Asphalt concrete<br>Soil cement<br>Bentonite clays<br>Chemical treatments<br>Waterborne treatments |                                                                                 |

Swelling of expansive clays or clayshales under the impoundment may also contribute to differential movement. If the entire site is underlain by expansive soil the heave may be fairly uniform and may not be of much concern. Also, in that case the soil would probably be sufficiently impermeable so as not to require that a liner be placed. If, however, discontinuities exist, such as contact zones between different dipping strata, some areas may heave and others may not. If heave is of a magnitude that could decrease the effectiveness of the liner, special design precautions may be necessary. It should be noted that seepage from the tailings is not necessary to cause swelling of expansive subsoils. The elimination of evapotranspiration from the surface and diffusion of water from greater depths may cause heaving.

In general, the potential for differential settlement to affect the liner would depend almost entirely on the nature of the foundation subsoils and the degree of pretreatment prior to construction of the liner.

Interaction with other failure mechanisms. Other failure mechanisms that may influence differential settlement of the subsoil foundation material are mainly those that may contribute water to the underlying soil. As such, any failure of the liner that may result in excessive seepage could contribute to the occurrence of differential settlement. However, not all soils exhibit settlement due to wetting and in some instances seepage may not contribute to settlement.

Methods of prediction. Methods of predicting the amount of differential settlement to be expected in the liner would follow similar analyses as discussed for predicting differential settlement of the cover. It should be emphasized that accurate prediction of differential settlement is highly dependent upon an adequate subsoil investigation and soil testing program during the design phase of the impoundment. Particular attention should be paid to detection of the existence of collapsing and compressible soils and irregular subsoil profiles.

Likelihood of failure. The likelihood of occurrence for differential settlement is very site specific. In general, the likelihood of differential settlement would increase as the depth to bedrock increases. Irregularity of the soil profile and erratic material properties will increase the likelihood of failure.

As for the cover, the liner will undoubtedly be designed to accommodate differential settlements of a magnitude predicted during the investigation. Consequently, the likelihood of failure will depend on the degree of conservativeness employed in the design and the variability of the subsurface soils and rocks.

Depending on the site characteristics, the likelihood of failure could range from a very low value up to a value reflecting almost certainty.

Magnitude of release. The release of radioactivity through a liner would be in the form of dissolved radioactive materials in seepage water. Prediction of the magnitude of release through a cracked liner is difficult. Attempts to bound the quantity of flow through the crack can be done utilizing Darcy's law and flow net analyses (Cedergren 1977, McWhorter and Sunada 1977). It is expected that the magnitude of release would not be great, that the release would fall within the lowest category of magnitude that is used.

In the case of a shear type displacement the magnitude of release would depend on the magnitude of displacement and the material used for the liner. If a synthetic material is used, and the magnitude of differential settlement does not cause rupture of the liner, obviously no release would occur. However, if the magnitude of differential settlement is greater than what could be tolerated by the synthetic liner, the magnitude of release would be a function of the area exposed by failure of the liner.

In a natural material, such as compacted bentonite, the likelihood of a tension crack failure would not be great because of plastic flow within the clay. If a shear type displacement occurs of a magnitude greater than the thickness of the liner, the magnitude of release would be a function of the area of the discontinuity that is exposed. On the other hand, complete disruption of the liner may not occur, but the effective thickness of the liner may decrease in the zone of differential settlement. In that case, the quantity of seepage through the liner would be computed on the basis of Darcy's law for the thinner zone and compared to the release that would occur for the situation where no liner existed. In most cases the magnitude of release is not expected to be large.

Site considerations. Site considerations that will influence the differential settlement are similar to those discussed for differential settlement of the cover. For impoundments of low height, only the subsoil conditions need to be considered. For higher impoundments the bedrock may need to be considered as well.

As discussed previously, differential settlement may be expected to be larger where the subsoil profile is irregular or where large differences in thickness and material types occur across the site.

Design considerations. The thickness of the liner and the nature of the material to be used must be selected so that it will not leak excessively under settlements of the magnitude to be expected. The thickness of the liner should be such that after differential settlement has occurred, a sufficient thickness would still exist to minimize the seepage to an acceptable value. In situations where differential settlement may exist, liners constructed of natural materials such as compacted bentonite have the advantage over synthetic liners in that they are "self-healing" and are not expected to fail if the thickness is greater than the shear displacement encountered.



TABLE A-3. Some causes of subsidence

- 
- 
1. Subterranean voids
    - a. Rock solution (limestone or dolomite areas)  
Sinkhole -- vertical  
Caverns -- vertical or horizontal  
-- may occupy one or more levels
    - b. Mines
    - c. Wells and drill holes
    - d. Volcanic deposits -- gas vents and voids
    - e. Cracks in foundation soils and rocks
  2. Collapsing soils -- low-density loess upon wetting
  3. Dispersive clay
  4. Piping (erosion tunnels)
  5. Soft clay deposits
  6. Organic soil deposits
  7. Removal of oil and gas deposits
  8. Lowering groundwater level
  9. Loose sands -- earthquakes
  10. Movement along faults
  11. Loading from the impoundment itself
  12. Collapse of underdrains, decant lines, etc.
- 
-

In addition, natural materials may flow laterally, under the vertical stresses imposed by the weight of the tailings above them. Tension cracks would, therefore, not occur in natural material liners due to uniformly distributed differential settlements. Clays of higher plasticity have both the advantage of being capable of flowing and also of being less permeable than less plastic clays.

Time dependence. Because differential settlement of the liner is due only to compression of the foundation materials, consolidation will occur faster than for the cover. If large deposits of soft, relatively impermeable foundation materials (i.e., clay) exist, consolidation may require up to about 100 years to be completed. However, for sandy clays or silts primary consolidation will occur in only a few years after abandonment. If the subsoils are very permeable, consolidation may have been completed by the end of tailings placement. Secondary consolidation and creep, however, may continue for considerably longer periods of time. If the deformation is due to creep of foundation materials or potential shear instability of the foundation materials, accelerated movements may occur even thousands of years after abandonment. In those cases where creep failure could occur, the impoundment could be redesigned to reduce the stresses in the foundation material. Differential movement due to swelling of expansive clays may require considerably longer periods of time. In that case, however, it is expected that differential movements would be completed within the short long-term period.

If collapsing soils are present, differential settlements may occur suddenly at almost any time within the lifetime of the impoundment. If the liner fails due to other mechanisms, the introduction of large quantities of seepage into the collapsing soils may result in an accelerated collapse of the soil, and more rapid differential settlement occurring at that time.

For long long-term considerations, it is expected that displacements will have stopped. After several thousand years have elapsed it is not expected that much water would remain in the tailings and seepage would be of little concern.

#### Subsidence of Subsoil and Rock

Cause and description. If localized subsidence of sursurface soil or rock below a tailings impoundment occurs, displacements may be induced that could cause failure of the liner. Subsidence at any site could develop from many causes, some of which are listed in Table A-3.

Interaction with other failure mechanisms. Subsidence may contribute to cracking and failure of the liner if differential settlement is relatively large and occurs across a short distance. Subsidence may also contribute to cracking and failure of the dam,

decant lines, underdrains, etc. Subsidence can also change the drainage features of the surface of the impoundment. Cracking of the liner and increased seepage may reduce the shear strength of foundation material. This can result in stability problems for the impoundment.

Failure of the liner due to other factors, such as horizontal movement along a fault, differential settlement, stretching or malfunction of the liner itself could cause increased seepage which in turn could create subsidence. Once a small crack forms, water moving through the crack (or cracks) may cause a further increase in seepage by enlarging the crack and subjecting the foundation material to wetting and erosion.

Methods of prediction. The possibility of subsidence is discussed in textbooks on Soil Mechanics and Geology (e.g., Terzaghi and Peck 1967, Mitchell 1976, Sowers and Sowers 1970, Bureau of Reclamation 1974, Thornbury 1969). However, methods to predict the amount and rate of subsidence from subterranean voids are unavailable. Methods to predict amount and rate of settlement of subsoil deposits from loading or removing water, oil or gas are also discussed in most textbooks in Soil Mechanics. Information about underlying geologic formations can suggest the chance for subsidence due to solution cavities. Knowledge of past underground mining activity in the site area could be used to predict potential for collapse due to loading the surface with impounded tailings.

Methods to predict amount and rate of movement from collapsing and swelling soils are in the process of development and only provide indications of the potential for collapse or swell. The same is true of tests on dispersive clays. Subsidence from earthquakes will be discussed at a later point.

Likelihood. Localized subsidence, as differentiated from differential settlement, that could cause failure of the liner (or embankment) will be very site and design specific. It will depend to a large extent on the foundation rocks and soils, the size and depth of the tailings impoundment and the nature of the tailings. The design of a liner to accommodate differential settlement caused by subsidence was discussed in the previous section.

Magnitude of release. The potential magnitude of movement of radioactive materials as a result of failure of the liner by subsidence is very site specific. The amount of release will be limited by a number of factors such as the location of the failure, the nature of the tailings, the backup control measures (e.g., underdrain below the liner to collect seepage), the permeability and types of natural soils and rocks below the liner, or the type of subsidence (total collapse of a large cavern forming a sinkhole versus uniform surface settlements).

Site considerations. Site considerations that will influence subsidence are primarily the subsurface soil and rock profile, level and change in level of the groundwater surface, the area and depth of the impoundments, and most conditions presented in Table A-3.

Time dependence. Subsidence due to collapse of underground voids is possible at any time during the short or medium long-term period. If it has not occurred within those time periods, it would not be expected to occur during the long long-term period.

#### Chemical Attack

Causes and description. No liner will be completely immune from chemical attack or weathering. The causes and nature of the chemical changes would be similar to those described previously for the cover.

Interaction with other failure mechanisms. A potential failure of the liner or underdrain system from any cause would contribute to potential chemical attack of the soils below. Possible changes in the subsurface material could lead to changes in permeability, strength or compressibility. Chemical attack can change the physical properties of the liner leading to a possible failure of the liner by shrinkage and/or changes in plasticity. This can lead to the development of cracks. On the other hand, the seepage of acidic water into the subsoils may cause a chemical change to clay minerals thereby decreasing the permeability. In that case the weathering would have a beneficial effect.

Methods of prediction. The amount and rate of chemical attack of the liner will be dependent on the type of liner, the pH of the water in the tailings, and the temperature. If the liner is made of clay, the type of clay minerals are important. Methods for analysis of chemical weathering are discussed in Gram (1968) and Mitchell (1976). Within the present state-of-the-art it is possible to predict the trends or effects of chemical attack on linings below saturated tailings, but the accuracy of such predictions is uncertain.

Likelihood. The likelihood of chemical attack of the liner would be high. A change of liner properties due to chemical changes is probable for liners containing tailings with high or low pH. The extent to which these changes would cause failure, however, will depend on the material or soil type, the thickness of the liner and the nature of the chemical change. Some liners may be very subject to chemical attacks under conditions occurring in an impoundment, whereas in others the effects may not be detrimental.

Magnitude of release. The magnitude of release will depend on the nature of the failure. If the chemical changes result only in a change of permeability, the seepage rates could be computed on the basis of Darcy's law and would be a function of the change of permeability.

If the chemical change destroys the liner the amount of release would depend on the size of the failure. The magnitude could vary from 0 (no change or decrease in permeability) to 100% of release by seepage (complete disintegration of the liner).

Since repair to the liner would be difficult to accomplish, the negative utility factor of a significant failure of the liner would be high.

Site considerations. The site conditions that will influence chemical attack of the liner are primarily the soil types available for construction, and the climatic conditions. The permeability and types of subsurface soils would also be important, since failure of the liner could subject them to chemical weathering. A site underlain by limestone, for example, would be very subject to chemical attack if the seepage was acidic.

Time dependence. The time needed for chemical attack of a liner (or any material) varies greatly. The thinner and more permeable that the liner is, the warmer the climate is, and the further the pH of the water is away from neutral, the faster the chemical attack will take place. In general, the time dependence would be the same as for chemical changes of the cover. It would be expected that all chemical changes would be completed within the short or medium long-term changes.

#### Embankment

##### Differential Settlement

Causes and description. Differential settlement of the embankment of a tailings impoundment may occur due to compression of either the foundation soil or the soil in the embankment itself. Differential settlement within the foundation soil will result from either uneven subsurface profiles or from variations in material properties.

The material from which the embankment itself is constructed would be of fairly uniform characteristics. However, differential settlement can occur within the embankment material if its height varies due to an uneven bedrock. For example, if the abutments for the embankment consist of steep or irregular bedrock such as a valley wall or a canyon wall, differential movements would be likely.

Damage to the embankment from differential settlement usually takes the form of cracking of the embankment. In some instances the cracks may be visible on the surface, but in other cases they may exist in the lower regions of the embankment and may not be visible.



In water impoundment dams, cracking is of particular concern because, if it leads to piping, total failure of the dam can result. In tailings dams the tailings themselves provide a filter over the crack and protect against piping. However, for uranium tailings dams, dissolved radionuclides can escape through the cracks. In addition, if the cracks continue to the surface, surface water erosion may be increased around the cracks.

Experience has indicated that cracking is more pronounced in dams that are constructed in areas having rainfall less than about 15 inches (Sherard 1973). The main reason for the greater incidence of cracking in arid regions is because the borrow of which the embankment is constructed is found in a dry condition and is hard to wet uniformly and adequately. As a result the embankment is non-uniform and brittle. The embankment soil cannot flow or creep as differential settlement takes place. In addition, the foundation materials in these areas are usually partially saturated and subject to settlement when wetted. Cracking of the embankment can also be caused by lateral displacement of the foundation soils under the weight of the embankment. Such cracks, however, are usually longitudinal cracks running parallel to the axis of the embankment. Those cracks may influence the stability of the dam, but contribute little to seepage.

Interaction with other failure mechanisms. Excessive seepage through the liner could induce settlement in foundation soils that were partially saturated initially. Also, erosion and gulying could cause stress concentrations in zones of the embankment that could then cause cracks to form. The latter effect, however, would be small.

If precipitation enters cracks pore water pressure can be induced that could reduce the stability of the embankment slopes.

Methods of prediction. Differential settlement due to consolidation of foundation materials can be predicted using one-dimensional consolidation theory. This has been discussed previously. Similar analyses can be applied to compute the vertical compression of the embankment. However, cracking in the embankment can occur even for relatively low values of crest settlement.

Attempts have also been made to predict displacement within embankments both vertically and horizontally by the use of the finite element method (Clough and Woodward 1967, Lee and Shen 1969). Such analyses provide the capability of determining displacements and stresses within the embankment for various material constitutive relationships. They do not, however, predict cracking within the dam. The magnitude and extent of cracking must be inferred from the computed displacements and engineering judgement regarding the nature of the embankment material.

Several case histories and some statistical results indicating the cracking of dams as related to construction practices and material properties are discussed in Sherard (1973). At the present time no mathematical model for prediction of locations and magnitudes of cracks exists.

Likelihood of failure. Because most uranium tailings impoundments are constructed in areas of relatively low annual rainfall, the likelihood that cracking will occur is relatively high. On the other hand, the extent to which such cracks would be continuous across the width of the embankment is uncertain. Furthermore, the deposition of coarse tailings near the face of the embankment helps to minimize the effect of cracking. Thus, although cracking will probably occur, the likelihood of failure may be classified as moderate.

Magnitude of release. Dissolved radionuclides will be released along with any seepage that would exist from cracks in the embankment. Some small amount of suspended tailings could also be carried out. If the cracking is of a high frequency and the cracks are relatively large, considerable amounts of seepage may be released. On the other hand, the tailings may fill the cracks and decrease the amount of seepage loss. Piping through cracks would not be expected to occur. Therefore, it is possible that the introduction of water into cracks that do form may soften the material around the cracks, thereby providing a self-healing mechanism to close the cracks.

The computation of a magnitude of release from cracking is difficult and largely subjective. It is expected that the magnitude of release through cracking would, in most cases, be low.

Site considerations. Differential settlement may be expected to be of concern over sites in which deep deposits of soft or potentially collapsing foundation soils exist. Sites in which the embankment would be constructed between steep bedrock abutments, particularly if steps or trenches in the bedrock exist, are more contributory to cracking. A major site consideration would be the existence of adequate borrow material to construct an embankment that is not particularly susceptible to cracking. Desirable characteristics of the borrow material will be discussed below with regard to design consideration.

An additional site consideration is climate. It was noted earlier that cracking is of more concern in areas where annual rainfall is low.

Design considerations. Cracking of embankments can be accentuated by the presence of zones of radically different materials within the embankment. Adequate transition zones should be provided between the core and shell of zone embankments. In homogeneous embankments this is of less concern.

The types of materials used for construction may also influence cracking. Residual soils and soils which assume a brittle nature after construction exhibit greater amounts of cracking (Sherard 1973).

Time dependence. Differential settlements of the embankment and foundation soils would be expected to be completed within a short long-term period. Experience has shown that if cracking is to be a problem it usually occurs earlier in the lifetime of the dam, within approximately ten years. In medium and long-term time periods creep may cause the soil to flow and close the cracking of the embankment. Also, after the tailings have dried, the seepage through cracks would not be of concern. Stability of the embankment, of course, would continue to be a potential problem.

### Slope Failure

Causes and descriptions. Slope failure of the embankment can occur as a result of several different factors. During operation of the tailings impoundment the primary cause of slope failures is the existence of a high phreatic line. After abandonment, however, the phreatic line would become lower. The exception to that would be if water could collect over the impoundment and seep into the tailings.

Another potential cause of slope failure would be the buildup of pore water pressures by precipitation entering cracks in the embankment.

A third cause of potential slope instability would be creep failure occurring within the slopes (Nelson and Thompson 1977). Creep failure results from continued deterioration of the soil strength as a result of creep strains that occur within the material.

Potential slope instability can also be caused by seismic events. Seismicity is discussed in a later section.

Interaction with other failure modes. Embankments should be designed to have flat slopes in order to minimize wind erosions. Flat slopes enhance slope stability as well and decrease the likelihood of occurrence of a creep failure within the embankment.

Differential settlement that could cause cracking of the embankment can promote progressive failure of embankments by the introduction of water into cracks.

Wind and water erosion can remove materials near the toe causing an increase in the steepness of the slope. If erosional processes continue to remove material, the stresses within the embankment can be increased to the point of failure.

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In general, factors that decrease the probability of other failure mechanisms also enhance the stability of the embankment. Failure mechanisms that can remove material and cause changes in the geometry of the embankment can contribute to slope instability.

Likelihood of failure. The likelihood of a slope failure occurring due to a high phreatic line would be very small provided that the embankment was kept drained. The likelihood of failure resulting from water entering the cracks would depend on the extent of maintenance on the site. However, even with minimal maintenance the likelihood of failure would be low to moderate. The failure of the embankment due to erosion at the toe is site specific. In that case likelihood of failure would be slightly less than the likelihood of occurrence of erosion.

The likelihood of failure occurring as a result of creep depends on the magnitude of stresses existing within the embankment. If stresses within the embankment are everywhere less than the residual strength of the soil, the probability of failure due to creep is very small. If, however, stresses in particular zones exceed the residual strength of the soil, progressive creep failure may occur after sufficiently long periods of time (Nelson and Thompson 1977). If the residual strength of the embankment soil is used for design the likelihood of creep failure would be minimal.

Magnitude of release. The magnitude of release resulting from slope failure of the face of the embankment would not be large. It is doubtful whether a slope failure would actually intersect the tailings except in the case of liquefaction during an earthquake. If instability of the embankment does occur, the face would slump and the unstable mass would assume a more stable configuration. The release would be small. If, however, further progressive failure can continue as a result of geometry changes caused by the initial slope failure, a larger release may be possible.

One instance in which relatively large amounts of radionuclides could be released would be if the tailings are saturated and the slope failure intersects them. Under those situations, liquefaction of the tailings can occur. This phenomenon would be similar to failure by overtopping of the embankment. Such failures have been observed to continue over several days. The flowing tailings can travel for distances on the order of miles depending on the slope of the downstream terrain.

Site considerations. The embankment may be designed and constructed around site features. Therefore, site considerations are usually not a limiting factor for embankment design, provided that construction material is available in the area.



If the foundation soils are weak, the stability of the embankment would be decreased unless the subsoils are stabilized. Another site consideration that may influence slope stability is the ability to route flood waters around the embankment so as not to cause erosion of the toe. Also, embankments should not be constructed over faults.

Design considerations. Design that is conducive to stability of the embankment utilizes flat slopes and the use of berms at the toe if necessary. From the standpoint of long-term creep failure the slopes should be designed such that the residual shear strength of the embankment soil is not exceeded. Although stresses in excess of the residual strength may be tolerated in some small zones, the embankment should not be designed on the basis of the peak strength of the soil.

Time dependence. If slope instability has not occurred by the time of abandonment of the site, it is not expected that slope instability would occur within the short long-term period. However, for medium and long long-term considerations, creep displacement can induce failure. Although creep may occur for time periods up to the long long-term (100,000 years), it is expected that other potential failure modes would be of more concern within that time period.

### Gullying

Causes and description. The cause of gully formation on the embankment of a tailings impoundment will be a combination of steepness of slope, concentration of runoff and erodibility of the soil. The most likely place for gullying to begin would be at the crest of the slope. At this point runoff from the cover would increase in erosive power as the gradient steepens. Gullying of the embankment could also be the result of the headward migration of gullies started from outside the impoundment. This may occur if runoff is concentrated around the embankment into a drainage along which the gully could advance.

Gullying of the embankment could result in significant radionuclide releases. Gullies are capable of moving significant quantities of material (Mabbut 1977, Schumm 1977). If it is allowed to grow, a gully could advance through an embankment into the tailings. If the embankment is breached, only the specific site conditions could predict the amount of tailings that would be carried downstream.

Interaction with other failure mechanisms. The interaction of gullying of the embankment with other failure mechanisms is the same as for gullying of the cover. Differential settlement may cause cracking or depressions that would concentrate runoff at specific points on the embankment increasing the potential for gullying. Gully formation on the cover could concentrate runoff and cause gully formation on the embankment. The reverse is also true. Any change in climate or vegetation cover could increase runoff or decrease stability and lead to gully formation on the embankment.



If the toe of the embankment is eroded and steepening of the slope results, the risk of gully formation will increase. The interaction of gullying with slope stability must also be considered. If enough material is removed by gullying, local slope instability could be created. This could remain a local problem or it could spread throughout the entire embankment.

Likelihood. The likelihood of gully formation on the embankment will be higher than for the cover because of the steeper slopes. In order to adequately predict the likelihood of gullying for short long-term periods, the site and design plan must be evaluated. This evaluation would consider:

1. Slope length and gradient
2. Vegetation cover or other stabilization measures
3. Embankment soil erodibility
4. Climate
5. Occurrence of gullying in similar natural settings in the immediate vicinity.

Over longer periods of time the likelihood for gully formation on the embankment will be relatively high.

Magnitude of release. The magnitude of release will be a function of the size and extent of the gully or gullies formed. Small gullies that are either repaired or reach a state of equilibrium might release little, if any, radionuclides. At the other extreme an extensive gully that continued to grow, cutting through the embankment and into the tailings, may result in extensive instability of the embankment. Extensive amounts of radioactive material could be released either by mobilization of tailings or by radon emanation. The magnitude of release is site specific and depends on the particular design of the impoundment. It can range from a low value to a high value depending upon the specific disposal plan.

Site considerations. Site considerations that will influence this potential failure mechanism are similar to those discussed for gully formation on the cover. In addition, consideration should be given to the area below the embankment. Existing slope, soil, and runoff conditions for that area should be analyzed for potential gully formation that could advance headward into the embankment. Also, changes that could occur in the area as a result of the impoundment should be analyzed.

Design considerations. The design of gentle embankment slopes and the avoidance of sharp breaks in slope between the cover and embankment are probably the most important design considerations for the reduction of gully potential. Grading to avoid concentration of runoff and construction of adequate diversion structures to eliminate off-site runoff are also important. If steep slopes are necessary because of topography or other design constraints, shortening of drainage paths by the use of terraces and diversion of runoff off the slopes should be considered. Vegetation or the inclusion of stones or cobbles in the soil matrix of the embankment could increase stability. Highly erodible soil should be avoided.

Time dependence. Gullies can form at any time during the history of the impoundment. There is no basic time dependence except that relative to likelihood. The longer the time span the greater is the chance that gullies will form. This is true for a non-changing environment, but even more important if climatic changes can be introduced with time. A change in climate can cause a stable situation to become unstable. The likelihood of climatic changes or variations should be considered to the extent that they could influence a particular disposal plan.

#### Water Sheet Erosion

Causes and description. The general causes of water sheet erosion of the embankment are similar to those discussed for the cover. The important difference is the slope of the embankment. On the cover, the slopes will be relatively gentle unless topographic constraints are encountered. For the embankment, however, the slopes are likely to be steeper and, therefore, more susceptible to water erosion.

Interaction with other failure mechanisms. Any failure mechanism that results in increased runoff or a concentration of runoff will interact to increase the water erosion potential of the embankment. These failure mechanisms include differential settlement, diversion structure failures, vegetation failure and climatic change. These factors are discussed in more detail with regard to water erosion of the cover. In addition, flood waters that come into contact with the toe of the embankment have the potential to erode and steepen the slope. If steepening occurs increased erosion is likely.

Likelihood. The likelihood of water erosion of the embankment will be the same as for the cover. Erosion will occur continuously. The likelihood of failure will increase continuously with time reflecting the time-related nature of this failure mechanism.

Magnitude of release. Erosion losses of soil from the embankment will increase radon emanation and gamma-ray emission to a lesser degree than with erosion of the cover. The reason for this is that the relative thickness of the embankment will be greater and the more highly radioactive slimes

portion of the tailings will generally be located in the central portions of the impoundment away from the embankment. However, if erosion is allowed to progress to the point where slope instability results, the potential release would be greater, as discussed in the previous section.

Site considerations. The important site considerations are the climatic conditions that relate to precipitation, and the runoff potential for upstream watersheds. These both relate to the amount of water that can come in contact with the embankment as runoff or precipitation. For long time spans the natural vegetation in the area is important because those types of vegetation will be established on the embankment.

Design considerations. Embankment design to control erosion potential should take into account the slope length and steepness. The use of terraces and water diversion schemes should be considered. Soil properties and vegetative cover will influence erosion. On steep embankment slopes where vegetation is more difficult to establish, consideration should be given to using rock and gravel to serve as a filter and riprap. This type of protection can be effective against water as well as wind erosion. The shape of the slope may also be an important design element. Research done on slope shapes conclude that on concave slopes sediment loss will be lower and the erosion depth will be shallower than with either a uniform or convex slope (Meyer et al. 1969).

Time dependence. As discussed previously, there is no basic time dependency related to water erosion failure. Erosion is a continuous process occurring throughout the time spans considered.

#### Wind Erosion

Causes and description. Wind erosion failure of the embankment is the result of wind detachment and transport of soil materials. The process elements and description are summarized by the wind soil loss equation presented previously with regard to the cover. Wind erosion of the embankment, however, may be more severe due to steeper slopes. The actual extent of erosion potential must be analyzed for each specific site and disposal plan. Wind erosion of the embankment can be localized in "blowouts" common in beach dunes, and similar in failure extent to water formed gullies.

Interaction with other failure mechanisms. If climatic conditions change resulting in higher winds than predicted, reduction or loss of vegetative cover, and/or loss of soil moisture, wind erosion will increase. If blowouts occur they have the potential to become large and interact with surface drainage, causing channeling. This could lead to enlargement by water erosion and the potential for significant losses of embankment and cover material, and tailings.

As with water erosion, any failure mechanism that increases the slope of the embankment, such as stream undercutting, increases the wind erosion potential. Furthermore, any failure that results in loss of vegetation or other protective covers (mulch, crusted surfaces, or riprap) from the embankment will interact to increase the wind erosion potential.

Likelihood. The likelihood that wind erosion will occur on an embankment is high and increases with time. The magnitude of release reflects the overall effect.

Magnitude of release. The magnitude of release due to wind erosion on the embankment will be based upon an estimate of embankment thickness lost and consequences of that loss. The potential soil loss and consequences of blowouts can only be subjectively evaluated.

Since calculated soil losses are the result of site specific evaluation only a general discussion of magnitude is possible. As for water erosion, wind erosion of the embankment is potentially greater than on the cover because of slope. However, this increased loss is mitigated by the greater thickness of soil in the embankment and the greater distance from the more highly radioactive slimes zone of the impoundment. In short or medium long-term periods erosion losses are expected to be relatively low. For the long long-term periods, wind erosion could remove the entire embankment and tailings pile if no maintenance is applied.

Site considerations. The most important site consideration is the direction and force of prevailing winds. If possible, the impoundment should be located so as to reduce exposure of embankment slopes to prevailing winds.

Design considerations. Design considerations for the control of wind erosion would be the use of gentle slopes, windbreaks, incorporation of gravel or cobbles in the soil matrix to provide armoring, and vegetation cover. In extreme cases, irrigation of the surface to control dryness or the use of chemical cementing agents may be required.

Time dependence. Wind erosion is a continuous process occurring throughout the time span being considered.

### Flooding

Causes and description. The general causes and descriptions of flood failure of the embankment are the same as the cover and have been discussed in that section. The basic natural phenomena of flooding will be discussed in a later section.



Interaction with other failure mechanisms. Failure of the embankment due to the occurrence of floods greater than the design flood for the impoundment will be influenced by several other failure mechanisms. The failure of diversion structures, erosion or gulying of the cover, gulying of the embankment, or differential settlement in the cover or in the embankment could result in concentration of flood waters. This concentration and increase in flow could result in overtopping and washout of the embankment. Erosion or differential settlement of the cover could form impoundments of water near the crest of the embankment. Flood waters so contained could raise the phreatic surface or cause overtopping at times of abnormally heavy precipitation.

Erosion or gulying on the embankment itself, as well as differential settlement or minor slope stability problems could remove protective vegetation or riprap. In that case, flood waters coming in contact with the toe or lower slopes of the embankment could result in serious erosion and undercutting of the slope. If the slopes are steepened from this erosion, gulying or slope stability failures could be accelerated.

Methods of prediction. Sediment carrying capacity of streams and erosional processes have been discussed in an ASCE manual on sedimentation (ASCE 1977). However, there is no method of analysis that can predict the amount of embankment material that may be removed during a flood. Estimates can be made from comparisons with damage to other types of embankments during flooding, but the predictions will be subjective.

Likelihood of occurrence. The likelihood of occurrence of a flood greater than the design flood for the impoundment for the short long-term period would be low because of design, maintenance and storm probabilities. For medium long-term considerations the likelihood of failure will be somewhat higher and will depend on the design considerations. For long long-term periods, however, it will be almost a certainty that extreme flooding would occur. If the impoundment is located in an area that is susceptible to flooding, the likelihood of failure is high.

Magnitude of release. The magnitude of release will be a function of the degree of damage to the embankment, the size of the flood, and the routing of the flood water. Moderate slope failures due to undercutting of the embankment could result in very little release. If flood waters are confined to flood plains and diverted away from the impoundment, a small amount of radionuclides would be released. Conversely, if large quantities of water either flow over or around the embankment, major portions of the tailings impoundment could be removed. In general, it can be assumed that any portion of the embankment that comes into contact with the flood waters will be removed. The consequences of that with regard to magnitude of release must be evaluated for each site on an individual basis.



Site considerations. Location of the site with respect to upstream drainage areas, size of the catchment areas above the site, climatic conditions, and location within flood plains are the basic considerations. In general, optimum locations would be high above potential flood plains or at the top of watersheds close to drainage divides. At the latter location the catchment area and runoff potential from higher portions of the drainage would be minimized.

It may be possible to locate the site so that floods will deposit rather than remove material. Careful analysis, however, would be needed to determine their potential.

Design considerations. Design consideration that could reduce the potential for flood damage to the embankment would be:

1. The use of riprap or other "armor" to protect slopes against flood erosion.
2. Location at sites that are not susceptible to flooding.
3. The use of flood diversion structures.

Monitoring, maintenance and remedial measures. Monitoring climate and precipitation/runoff could provide information about the adequacy of original flood protection design. Such monitoring would identify changing conditions or add to the existing data base used to evaluate flood probabilities. If failure due to flooding did occur it would occur suddenly. Therefore, there is no directly applicable monitoring scheme that could predict potential flood damage.

Time dependence. Although the likelihood of occurrence of a major event greater than the design magnitude is small, such an event can occur at any time during the lifetime of the impoundment. The likelihood of occurrence will increase in direct proportion to the length of time period in consideration. However, at any particular time, the probability of occurrence in the year immediately following is the same whether it be the initial one hundred or initial one thousand year period.

#### Weathering and Chemical Attack

Causes and description. Weathering and chemical attack of the embankment soils may alter its chemical and physical properties. These processes may be physical, chemical or biological. Changes occur because a soil is unstable if certain conditions change. Those changes may occur in temperature, pressure, chemistry or pH. Basically, there are two types of weathering:

Physical weathering is a grinding or shattering action that reduces particle size, but does not change mineral composition.  
Physical processes include:

1. loading
2. temperature expansion
3. crystal growth (e.g., ice and salt in cracks of rocks)
4. colloid plucking (e.g., lichens curl up and dry and pull out pieces of rocks).

Generally, silt, sand and gravel-sized particles are formed by physical weathering.

Chemical weathering yields an increase in bulk of rock, smaller particle size, and a more stable mineral composition.

Chemical processes include:

1. Hydration -- the chemical addition of water to minerals (this must be distinguished from the free water that causes physical weathering). An important hydration example is the decomposition of feldspar mineral in granite to form the clay mineral, kaolinite.
2. Oxidation -- addition of oxygen ions to the minerals composing the rock. Rocks containing iron are greatly affected by oxidation.
3. Reduction -- the opposite of oxidation. The oxygen ions are removed from the minerals in rock.
4. Solution by carbonation -- solution of the rock material by water containing a considerable amount of carbon dioxide. This is particularly detrimental to limestone.

Generally, clay-sized particles are formed by chemical weathering. Factors influencing the rate of weathering and nature of the products include climate (temperature and rainfall), time, mineralogical composition, vegetation, drainage, and bacterial activity.

Physical and chemical weathering of the embankment would be greatest near the surface. It may decrease the permeability, increase compressibility and decrease strength. On the other hand, cementation of particles may increase the strength of the embankment. Leaching and ion exchange from water flowing through the embankment may also alter the physical properties of the embankment. Weathering of illites and the release of potassium may result in cracking of the soil.

The effect of low level radiation on the exchange of capacity and behavior of clays is unknown. Physical and chemical weathering of the tailings may occur and lead to physical property changes. Chemical weathering has been discussed in more detail with regard to the cover and the liner.

Interaction with other failures mechanisms. Seepage from a failure of the lining behind an embankment may contribute to increased weathering of the embankment. Weathering of the embankment may lead to changes in stability, settlements, and increased or decreased wind erosion. Stability reduction or settlement may lead to movement and cracking of the liner or cover and may cause failure of the liner or cover.

Method of prediction. Some minerals are particularly susceptible to rapid weathering. Materials that commonly degrade are shales, siltstones, mudstones, feldspars, and pyrite. The long-term characteristics of weathering materials is difficult to determine, but accelerated degradation tests could indicate the general trend.

It is usually considered good engineering practice to use embankment materials with a low susceptibility to weathering.

Likelihood. The likelihood of occurrence of weathering is great. However, with proper selection of embankment material the likelihood of physical weathering being of the magnitude great enough to allow major amount of undesirable soil property changes is small.

Magnitude of release. The magnitude of release will depend on the changes that occur due to weathering. For example, if the permeability changes, the amount of seepage will change in proportion to the change in permeability. If the weathering contributes to slope instability, the magnitude of release would be as discussed previously with regard to stability failures.

Site considerations. Site conditions that will influence weathering of the embankment are primarily the soil types available at the site embankment construction, the climate and the process used to leach the uranium.

Time dependence. The time needed for weathering of soils varies greatly. The warmer that the climate is, the more moisture that is available and the further the pH of the seepage is from neutral, the faster that weathering will occur. Freeze-thaw cycles will also increase the rate of physical weathering. The type of soil will greatly influence the rate of weathering. Failure of the embankment due to weathering is expected to be a long long-term phenomenon with little effect over shorter periods of time.

## Revegetation

### Fire

Causes and description. Fires can be caused by either human activity or natural events. Lightning is a natural fire-causing agent and is the most probable long-term cause of fires that can affect the impoundment. Fire potential is a function of climate, thunderstorm frequency, and vegetation. The direct effect of fire is the destruction of living and dead vegetation. Indirectly, fire will affect wind erosion and water erosion potential.

Interaction with other failure mechanisms. By itself, destruction of the vegetative cover may not be significant. It is significant, however, to the extent that it affects water erosion, wind erosion and runoff. Any change, removal or reduction in vegetation cover can increase erosion and runoff.

Fire destruction must be considered for the entire watershed in which an impoundment is located. Removal of vegetation by fire can affect the regional runoff, sediment yield, and flood characteristics. These changes could have significant impacts on the impoundment area.

Likelihood. The likelihood of fire related to failure of vegetation will be high for the long periods of time being considered.

Magnitude of release. In order to evaluate the magnitude of release related to failure of vegetation by fire, estimates must be made of the potential erosional and flood consequences. From the estimates, the potential magnitude of release can be established. Magnitude of release by erosional mechanisms has been discussed previously.

Generally, the magnitudes of release will be small if erosion rates are low and natural revegetation can occur quickly. If the fire is followed by extreme precipitation or wind storms, however, erosion rates could be high.

Site considerations. In order to reduce the potential for lightning striking the impoundment it should not be located on a high place relative to the surrounding topography. The fuel quality of native vegetation will indicate whether a site would have a high fire potential. Microclimates, such as southern versus northern exposures, will relate to moisture regimes and, therefore, influence fire potential. The likely path along which a fire could spread should also be considered.

Design considerations. The short long-term periods of fire potential may be influenced by the selection of fire resistant or low fuel revegetation species. Over the longer time spans, however, native species would invade the impoundment and control the fuel quality.



Time dependence. The likelihood that a fire will occur and destroy impoundment vegetation increases as the time period of consideration increases. The calculated fire occurrence defines the long-term probability that a fire will occur. As with floods, the likelihood that fire will occur on any given day will be the calculated probability.

### Climatic Changes

Causes and description. Climatic factors such as moisture, temperature, light and wind exert a limiting effect on plant life. Although they can stand some variations, all plants have an upper limit and a lower limit of tolerance to a change in climatic factors (Odum 1959).

Two levels of climatic change exist. First, there are very short-term changes such as drought which occur frequently, but last for only a few years within a region. Second are long-term gradual changes in world climate which may cause glacial advances or changes in sea level.

Vegetation is most sensitive to variations in temperature and moisture. These two factors interact within an area to produce the limits of climate which a plant species must tolerate. Lack of moisture or drought is the biggest problem associated with climatic change.

Cyclical or short-term drought will change the vigor and percent cover of vegetation. It may also influence the mixture of species that will develop on a short-term basis. Cyclical drought could be severe enough to destroy significant portions of the living vegetation. At any given point in time the effect of either drought type will be the same with respect to interactive failure mechanisms. However, permanent changes in vegetation for the medium and long long-term period have potentially more serious consequences.

Vegetation has lower limits of tolerance to climatic change on disturbed soils than on natural soils (Curry 1975). This phenomenon is caused by the destruction of the fabric of the topsoil which alters the biological, physical, and chemical characteristics of the soil. Climate input from man such as irrigation may establish species that cannot adapt to variations in the natural climate over short-term periods or may not succeed in the same manner as natural species over long-term periods.

Interaction with other failure mechanisms. Failures of vegetation caused by climate change interact with wind erosion, water erosion and flood failure potentials. Drought caused by permanent climatic change is most serious because this results in permanent changes in the erosional process. The likely interactions are fully discussed with regard to failure of vegetation due to fire.



A climatic change could result in the succession of a deep rooted plant species which could result in uptake of radionuclides by the plants. Thick vegetation could also cause an obstruction of water diversion facilities.

Methods of prediction. Short-term climatic cycles can be predicted from historic records on a regional basis. These predictions or forecasts must be evaluated in light of confidence limits for the data base used.

Long-term global climatic changes which cause major glacial advances may be predictable with the "astronomical" or Milankovitch theory (Calder 1978). The long-term projection is for the earth to warm due to the "greenhouse" effect and then to cool into another ice age over the long long-term periods due to variations in the earth's orientation with the sun.

The best basis for evaluation of the effects of these changes may be the development of future scenarios, evaluating the consequences of each.

Likelihood. The likelihood that failures in vegetation due to climatic change will occur over an extended time frame is high. The extent and duration of a drought and its resulting effect on vegetation must be determined based upon local climatic conditions, historical drought cycles and scenarios about future climate.

Magnitude of release. The potential of release due to a climatic change which affects vegetation comes from two sources: (1) failure of the vegetative cover may cause other failure mechanisms to occur, or (2) success of species which can concentrate radiation in its cells.

The magnitude of release due to failure of vegetation because of cyclical drought is the same as described for fire caused failure of vegetation. In the case of drought caused by permanent climate change, the magnitudes for long long-term periods can be relatively high. In this situation, loss or change of permanent vegetation can potentially result in significant increases in erosion rates and flood potential and magnitude. Reliable estimates of magnitude, changes in erosion rates and flood potential must be evaluated on the basis of predicted climate and vegetation changes.

It has been stated that certain deep rooted plants such as pines can concentrate uranium within its cells (Odum 1959). Although the magnitude of release is small, this type of release may come more directly into contact with other life.

Site considerations. Consideration of site characteristics that favor establishment of drought resistant native vegetation is appropriate. Site considerations with respect to erosion and flood potential are also important because of the interaction of vegetation with these failure mechanisms. Any site feature that minimizes drought effect, such as exposure, elevation or relief may be effectively combined to reduce drought impact.

Design considerations. Revegetation planning should consider the use of drought resistant species. This may be effective for the short long-term period. However, for long time periods native vegetation will invade the area and be predominant. Grading to conserve moisture and to capture runoff could be used to reduce drought effects. All design considerations that were presented for wind erosion, water erosion, and flood should be considered because of the high interaction of vegetation failure with these failure mechanisms.

Time dependency. Drought may occur at any point in the time span considered. Cyclical drought frequency may be identified and its timing predicted. Over long periods, droughts must be expected with varying intensities. Variation will be based upon the fluctuations of climate.

#### Water Diversion Structures

##### Slope Failure

Causes and description. Water diversion structures would have been constructed and been in use since the beginning of deposition of tailings in the impoundment. Therefore, in most cases, the short-term stability would have been proven and only long-term stability of slopes above the water diversion structures and canals would be of concern.

Many cases have been cited in the literature of slopes having failed several years after construction. The time period for these long-term failures ranges from less than 100 years (Casagrande 1949, Skempton 1964, Lambe and Associates 1973) to about 1000 years (Crawford and Eden 1967). A review of several long-term instability considerations in case histories is presented in Nelson and Thompson (1974).

Long-term instability may result from one or both of two mechanisms. When a slope is cut in overconsolidated clay or clayshale, negative pore water pressure may be induced. These negative pore water pressures result in an increase in the effective stress within the slope and an increase in stability. Dissipation of the pore pressures occurs over some time period resulting in a gradual decrease in the shear strength of the soils (Eigenbrod 1975, Vaughan and Walbancke 1973). The other factor that can cause instability is the existence of creep strains occurring within the soil. Accelerated creep and subsequent failure may occur after sufficient deterioration of the soil strength (Campanella and Vaid 1974, Nelson and Thompson 1977).

These mechanisms are of concern in clays and clayshales. In sandy soils long-term stability does not differ appreciably from short-term stability except as it is affected by erosion.

Interaction with other failure mechanisms. Other failure mechanisms would not contribute to long-term failure of slopes around diversion ditches. However, failure of diversion ditches could disrupt flood routing and could enhance erosion of the impoundment.

Likelihood of failure. The likelihood of failure due to slumping of the slopes above the diversion ditches is of concern primarily in over-consolidated clays and clayshales only. Its occurrence will depend on the rate of dissipation of pore water pressures and the creep characteristics of the materials. If the structures are adequately designed, however, it is expected that the likelihood of failure would be small.

Magnitude of radiation release. No direct release could result from failure of water diversion structures. The release would result only because this failure mechanism is coupled with other potential failure mechanisms. Thus, the magnitude of release must be considered in context with the potential failure mechanism (e.g., erosion of the embankment toe, erosion of the cover, impoundment of waters, etc.) that it accelerates.

Site considerations. This failure mechanism is obviously of concern only for sites requiring relatively large slopes above diversion ditches or extensive water diversion systems. Furthermore, it is of concern only in areas where materials conducive to long-term instability exist. Those materials are relatively impermeable materials. Their properties are characterized by a high peak shear strength relative to the residual shear strength. Materials of this type are commonly over-consolidated clays and clayshales.

Time dependence. Equilibration of pore water pressures would probably occur within a short long-term period. On the other hand, creep failures may occur at any time from the short long-term up to the long long-term time periods. Furthermore, since it has been shown that the creep rates will decrease to a particular minimum value prior to the onset of the accelerated creep (Campanella and Vaid 1974), the fact that slopes may be decreasing in rate of movement does not indicate that potential long-term instability does not exist. However, after the onset of accelerated creep, actual slope failure does not occur until some time later (Nelson and Thompson 1977). Therefore, if accelerated movements are detected, there does exist some time period within which remedial measures and maintenance can be taken.

### Obstruction

Causes and description. Obstruction failures of water diversion structures may occur from three major sources: soil, ice and vegetation. Each of these mechanisms can cause a partial or total restriction, thus reducing the water carrying capacity of the facility.

Soil obstructions can occur in two ways, either as a buildup in a sediment or as a landslide into a diversion channel. Sedimentation is caused by more soil particles being transported into the channel than is removed by erosion by the water in the channel. The soil can be transported into the channel by the bedload of an intercepted stream, by mechanical weathering, by erosion along the banks of the channel, or by windblown sediments. The accumulation of sediments is a function of the amount and particle size distribution of the sediments and the velocity of flow. The velocity of flow is a function of the quantity of water, the area of the channel, the slope of the channel, and the roughness of the channel perimeter.

Landslides which involve a mass soil movement into a channel can occur as a result of bank slope instability as discussed in the previous section or as a geologic phenomenon in rocks or soils above the facility.

Ice and snow accumulation can also cause obstruction to water diversion structures. Ice blockage can occur as a buildup in facilities such as pipes, open channels, or spillways. The buildup can cause a blockage during extended cold periods or can cause blockage as ice jams when snow melting occurs. In cold climates snow accumulations can cause almost complete flow restriction during the early weeks of the annual spring thaw. Glacial activity could be an additional source of ice obstruction in water diversion facilities.

The third source of obstruction is vegetation. Both living and dead vegetation are potential problems. Trees and shrubs can root and grow along channel banks. During extended periods of low flow, they can develop within the channel bottom. Within the channel, they reduce flow and provide places for waterborne objects such as dead vegetation to accumulate. Grasses and other ground cover can also increase the roughness of a channel and reduce flow.

Dead vegetation can be carried into water diversion works by winds, water, or by animals and man. Floods typically carry large amounts of dead trees and assorted vegetation into water courses which can cause blockage. Banana leaves carried by flood water posed a problem at one tailings dam in the Phillipines (Brawner 1978). Animals such as beavers and muskrats can build dams in diversion canals from vegetation and mud. Man-caused blockages can be caused by fences or discarded material in channels.

Interaction with other failure mechanisms. Obstruction of water diversion facilities can cause failure of tailings impoundments due to gullyng, sheet erosion or overtopping.



Methods of prediction. Methods of predicting sedimentation and erosion of channels have been discussed by Einstein (1950), Colby (1956), Colby and Hubbell (1961), and Simons and Albertson (1958). These techniques are based on modeling the velocity of flow, the amount of solids and the settling velocity of the particles. The amount of solids and particle size distribution can be predicted by comparative analysis of bedloads carried by streams in the area. Velocity prediction is based on the estimated quantity of flow, the slope of the channel, the area of the channel cross-section, and roughness of the channel. A model can then be developed based on an energy balance in the stream or canal.

Slope stability analysis and prediction was discussed in the previous section. Landslide potential above the ditches can be evaluated by a geotechnical engineering analysis of the slopes above the facilities.

Short-term ice and snow obstruction potential can be predicted from a knowledge of local climate, projected weather patterns, and experience of others operating water diversion facilities such as highway maintenance personnel or local irrigators.

A field study of natural vegetation recovery along old roads, canals, and abandoned disturbances can be useful tools in predicting the types and quantities of vegetation that will invade new diversion canals in the short and long-term. A field assessment is also useful in predicting vegetation that may be transported into the facilities.

Likelihood. The likelihood of obstruction of water diversion facilities is great. Inspection and maintenance at frequent intervals will be required to prevent failure. Depending on the design and site conditions and the secondary effects of flood routing, failure of water diversion facilities may or may not cause a release of tailings or radionuclides. Thus, the likelihood of failure could assume either a high or a low value.

Magnitude of release. The potential magnitude of release due to a water diversion obstruction failure is site and event specific. The release will depend on the exact location of the obstruction, the quantity of water that is diverted to an unplanned location, and the susceptibility of that location to water-induced failure mechanisms. The largest potential for release would be during the occurrence of a larger flood than the tailings impoundment can store or bypass by alternate means. An overtopping failure and removal of the embankment could release 50 to 60% of the tailings during the initial event and eventually all of the tailings if the dam breach was not corrected.

Site considerations. Site considerations that will influence obstruction potential of diversion facilities are climate, topography, geology, and hydrology. The interrelationships between these factors at each site will determine the obstruction potential of a planned diversion facility.



In general, the smaller the drainage area above a tailings impoundment in relation to the size of the impoundment, the safer the impoundment site against overtopping. Flatter terrain is most often less susceptible to landslides. Drier climates are less conducive to vegetation obstruction, but may be more susceptible to windblown sedimentation.

Time dependence. Sedimentation and deterioration of water diversion structures may occur continuously, but other mechanisms could cause obstruction at any time after construction. The likelihood of an obstruction occurring in the short to medium long-term periods is high unless some maintenance is performed.

APPENDIX B

RATING SCALES

## RATING SCALES

### EARTHQUAKES: INTENSITY AND MAGNITUDE

Two scales, the Modified Mercalli Scale and the Richter Scale, are often used in earthquake engineering.

#### Modified Mercalli Scale

The Modified Mercalli Scale (Table B-1) subjectively rates the intensity of an earthquake. The criterion that determines the intensity is the damage caused by the earthquake. A given earthquake can have many different intensities according to this scale. Intensity depends on the location and the damage caused at that location.

#### Richter Scale

The Richter Scale (Table B-2) rates the magnitude of an earthquake. An earthquake has only one magnitude. The magnitude is a measure of the total energy released by the earthquake. The magnitude rates the earthquake as a whole, independent of its effects at any particular point.

The scale is logarithmic and it is open at both ends. An increase in magnitude of one unit results in a thirty-fold increase in released energy. The relationship between the energy release and the magnitude (M) is:

$$\log E = 11.4 + 1.5 M$$

where E is energy in ergs (B-1). The largest Richter magnitude ever assigned to an earthquake was 8.9. At the other extreme, the smallest earthquakes felt by humans have magnitudes of slightly less than 2. There is about a billion-fold difference in the amount of energy released by earthquakes at these two extremes.

#### Comparing the Two Scales

Moderate-to-strong intensities on the Modified Mercalli Scale (IV and V) are thought to be equivalent to a Richter magnitude of 4.3 to 4.8. Destructive to disastrous intensities (VIII, IX and X) are possibly equivalent to magnitudes of 6.2 to 7.3 (B-2). Figure B-1 presents a more complete comparison.

- 
- I Not felt except by a very few under especially favorable circumstances.
  - II Felt only by a few persons at rest, especially on upper floors of buildings. Delicately suspended objects may swing.
  - III Felt quite noticeably, especially on upper floors of buildings, but many people do not recognize it as an earthquake. Standing motor cars may rock slightly. Vibration like passing of truck. Duration estimated.
  - IV During the day felt indoors by many, outdoors by few. At night some awakened. Dishes, windows, doors disturbed; walls make cracking sound. - Sensation like heavy truck striking building. Standing motor cars rocked noticeably.
  - V Felt by nearly everyone, many awakened. Some dishes, windows, etc., broken; a few instances of cracked plaster; unstable objects overturned. Disturbances of trees, poles, and other tall objects sometimes noticed. Pendulum clocks may stop.
  - VI Felt by all, many frightened and run outdoors. Some heavy furniture moved; a few instances of fallen plaster or damaged chimneys. Damage slight.
  - VII Everybody runs outdoors. Damage negligible in buildings of good design and construction; slight to moderate in well-built ordinary structures; considerable in poorly built or badly designed structures; some chimneys broken. Noticed by persons driving motor cars.
  - VIII Damage slight in specially designed structures; considerable in ordinary substantial buildings, with partial collapse; great in poorly built structures. Panel walls thrown out of frame structures. Fall of chimneys, factory stacks, columns, monuments, walls. Heavy furniture overturned. Sand and mud ejected in small amounts. Changes in well water. Persons driving motor cars disturbed.
  - IX Damage considerable in specially designed structures; well-designed frame structures thrown out of plumb; great in substantial buildings, with partial collapse. Buildings shifted off foundations. Ground cracked conspicuously. Underground pipes broken.
  - X Some well-built wooden structures destroyed; most masonry and frame structures destroyed with foundations; ground badly cracked. Rails bent. Landslides considerable from river banks and steep slopes. - Shifted sand and mud. Water splashed (slopped) over banks.
  - XI Few, if any (masonry) structures remain standing. Bridges destroyed. Broad fissures in ground. Underground pipelines completely out of service. Earth slumps and land slips in soft ground. Rails bent greatly.
  - XII Damage total. Practically all works of construction are damaged greatly or destroyed. Waves seen on ground surface. Lines of sight and level are distorted. Objects are thrown into the air.
- 

TABLE B-1. Modified Mercalli (MM) intensity scale of 1931 (B-1)

| MAGNITUDE | DESCRIPTION                                                                               |
|-----------|-------------------------------------------------------------------------------------------|
| 1         | Detectable only by instruments                                                            |
| 2         | Barely perceptible, even near epicentre                                                   |
| 4.5       | Detectable within 20 miles of epicentre,<br>possible slight damage within a small<br>area |
| 6         | Moderately destructive                                                                    |
| 7         | A major earthquake                                                                        |
| 8         | A great earthquake                                                                        |

TABLE B-2. Description of earthquake of selected Richter Scale magnitudes (B-3)



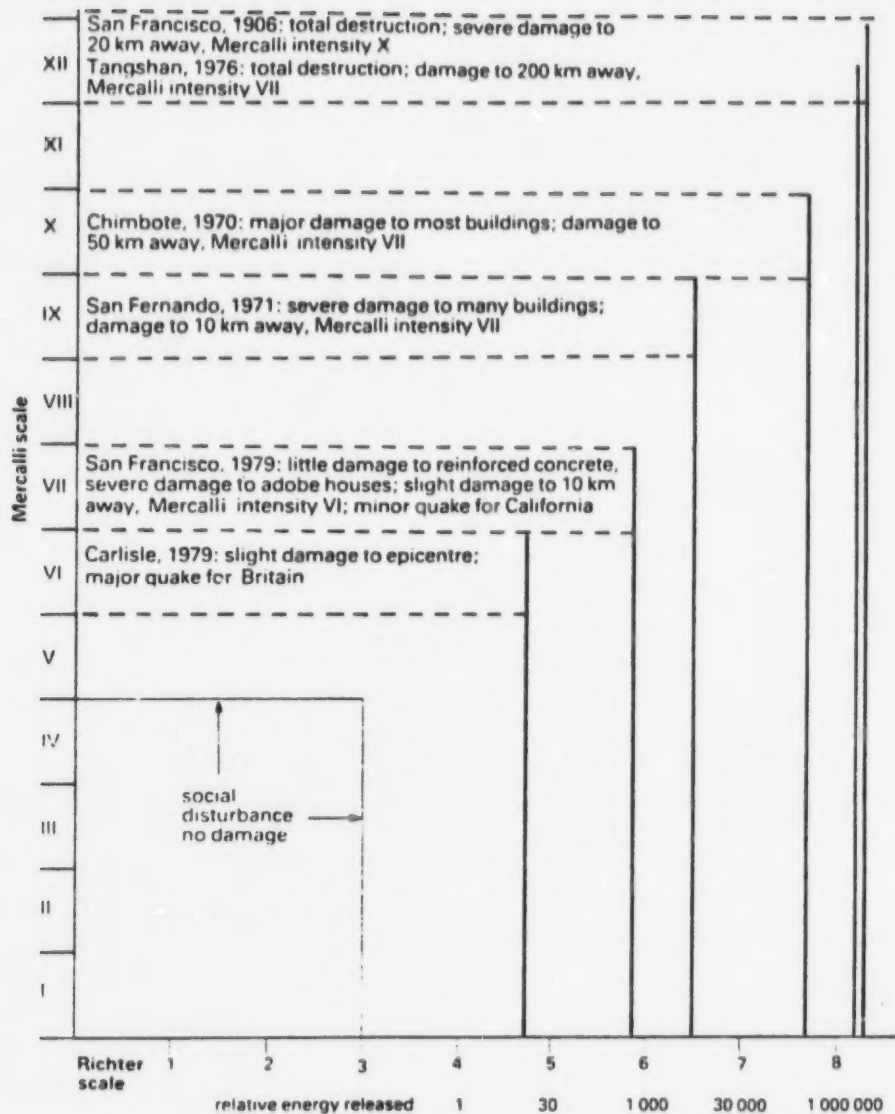


Figure B-1. Approximate correlation of earthquake damage, magnitude and intensity (B-4).

WIND: SPEED AND DAMAGE DONE

Beaufort Scale

The Beaufort Scale (Table B-3) rates winds by their speeds.

F-(Fujita) Scale

In 1971 a rating scale for tornadoes, called the F-Scale, was developed by Fujita (Table B-4). Ratings are based on the severity of damage and are related to maximum windspeed. Since 1971, all tornadoes have been rated according to the F-Scale (B-1).

| Degree | Wind speed<br>[ms <sup>-1</sup> ] | Description of wind | Wind effects                                                                                    |
|--------|-----------------------------------|---------------------|-------------------------------------------------------------------------------------------------|
| 0      | 0-0.5                             | Calm                |                                                                                                 |
| 1      | 0.5-1.7                           | Light airs          | Smoke rises nearly vertically                                                                   |
| 2      | 1.7-3.3                           | Light breeze        | Wind felt on face                                                                               |
| 3      | 3.3-5.2                           | Gentle breeze       | Leaves move                                                                                     |
| 4      | 5.2-7.4                           | Moderate breeze     | Small branches move,<br>wind extends flags                                                      |
| 5      | 7.4-9.8                           | Fresh breeze        | Large branches also move                                                                        |
| 6      | 9.8-12.4                          | Strong breeze       | Saplings move                                                                                   |
| 7      | 12.4-15.2                         | Light gale          | Strong branches bend,<br>wind is heard in buildings                                             |
| 8      | 15.2-18.2                         | Moderate gale       | Impeded walking, branches<br>break, tree-trunks sway                                            |
| 9      | 18.2-21.5                         | Fresh gale          | Wind displaces lighter<br>objects, strong branches<br>and saplings break, damage<br>to chimneys |
| 10     | 21.5-25.1                         | Strong gale         | Trees are uprooted, telegraph<br>poles break                                                    |
| 11     | 25.1-29                           | Destructive gale    | Severe damage                                                                                   |
| 12     | 29 and over                       | Hurricane           | Disastrous damage                                                                               |

TABLE B-3. The Beaufort Scale (B-5)

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|    |                                                                                                                                                                                                                                                                                                                                                                                                                                                                        |
|----|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| F0 | (64-115 km/h) T.V. antennae bent. A few roof shingles removed from houses and roofing stripped from barns. Patches of siding removed from houses, awnings or canopies damaged. Aluminum garden sheds moved or buckled and garden furniture blown around. Fences blown down. Trees broken or uprooted (intermittently in heavily treed bush lots).                                                                                                                      |
| F1 | (116-179 km/h) Large areas of roofing material stripped from homes or industrial buildings. Barn roofs entirely removed and boards or siding removed from barn walls. Some impact damage from flying missiles. Unanchored buildings twisted on their foundations. Steel hydro-electric transmission towers knocked down. Summer cottages move off their foundation.                                                                                                    |
| F2 | (180-251 km/h) Structural failure of roofs and porches. Barns demolished to the foundation. Empty stave concrete silos blown over or the upper portions of partly filled stave silos demolished. Unanchored 1-storey houses moved entirely off their foundation. Cottages rolled over or carried short distances. Farm wagons or equipment carried short distances. Areas of total damage in heavily treed bush lots. Considerable impact damage from flying missiles. |
| F3 | (252-330 km/h) Upper storeys of brick houses destroyed. Extensive structural damage to frame houses. Heavy farm machinery and automobiles moved or upset. Unanchored 2-storey frame houses moved entirely off their foundation. Tombstones blown over or carried short distances. House trailers entirely demolished. Extensive impact damage from flying missiles.                                                                                                    |
| F4 | (331-416 km/h) Two-storey brick homes almost completely destroyed. Empty poured concrete silos blown down. Automobiles, vans, heavy farm equipment carried long distances through the air. Extensive structural failure of industrial buildings.                                                                                                                                                                                                                       |
| F5 | (417-509 km/h) Little remains intact.                                                                                                                                                                                                                                                                                                                                                                                                                                  |

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TABLE B-4. The F-Scale for tornadoes (B-6)

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APPENDIX C

MODEL TAILINGS IMPOUNDMENTS

## MODEL TAILINGS IMPOUNDMENTS

The physical characteristics of uranium mill tailings piles in Elliot Lake, northern Saskatchewan, and Bancroft differ from site to site. Every pile is unique. To simplify analysis of these tailings, the following models can be used; all the tailings of any one region (e.g. Elliot Lake) are represented by one model. The figures and most of the description for the Elliot Lake and Saskatchewan regions, are from a report prepared by Kilborn for the NUTP (C-1).

### ELLIOT LAKE

Figures C-1 and C-2 show the Elliot Lake model impoundment.

Tailings storage is within a typical Elliot Lake area lake basin (C-1). Approximately one-half of the total tailings volume over the design life is stored below the original water level with the remainder above and around the lake surface. In this model, it is assumed that the lake exists within a steep-walled basin and inlet and outlet channels requiring dykes are through narrow, steep-sided valleys. These assumed conditions result in minimal dyke construction (C-1).

The Kilborn report lists construction and required structures completed prior to mill start-up. The following structures from the list will probably be present after closeout:

- three small dykes
  - i) 100 m long and 15.5 m high
  - ii) 50 m long and 9.5 m high
  - iii) 20 m long and 4.5 m high
- one kilometre freshwater diversion channel

The construction of the three small dyke sections includes a coarse till shell, low permeability till core, sand filter drain and interior and exterior slope protection (C-1).

Note that many long and high dykes are used at Nordic (Rio Algom) and Stanrock (Denison).

Kilborn also lists the tailings basin characteristics. The following are those that are significant in the closeout stage:

- interior and exterior dyke slopes: 2.5:1
- final tailings area: 200 ha
- final maximum tailings depth: 28 m
- watershed area: 700 ha
- total bulk tailings volume in pond at end of life: 50 000 000 m<sup>3</sup>
- tailings bulk density: 1.6 t/m<sup>3</sup>
- runoff coefficient for lake and watershed (ratio of runoff to precipitation): 0.7

#### SASKATCHEWAN

The model tailings containment basin is shown in Figures C-3 and C-4.

The Kilborn report states that the tailings containment basin is constructed on gently rolling topography similar to the southern portion of the Athabasca basin of north-central Saskatchewan. The surface landscape is composed of glacially-deposited sand and sand-till features combined with scattered lakes and muskeg depressions. Bedrock is assumed to be well below any required excavations.

Construction of the tailings basin is along a shallow hillside in order to utilize excavated materials for embankment construction. The method of tailings deposition is the sub-aerial technique incorporating an extensive underdrainage system beneath the entire base of the facility. The bottom of the basin is covered by a graded underseal with a filter blanket and perforated drainage system overlying this seal. The underdrainage system serves to intercept all seepage from the base of the tailings and, by removing any build-up of head within the filter blanket, significantly reduces seepage across the seal. The underseal beneath the facility, and seals within the main embankment, are constructed by in-situ modification of the till material with bentonite, moisture conditioning and compaction (C-1).

In the closeout stage the tailings may have a layered till and till-clay cover.

The Kilborn report lists some tailings basin characteristics. The following are those that are significant in the closeout stage:

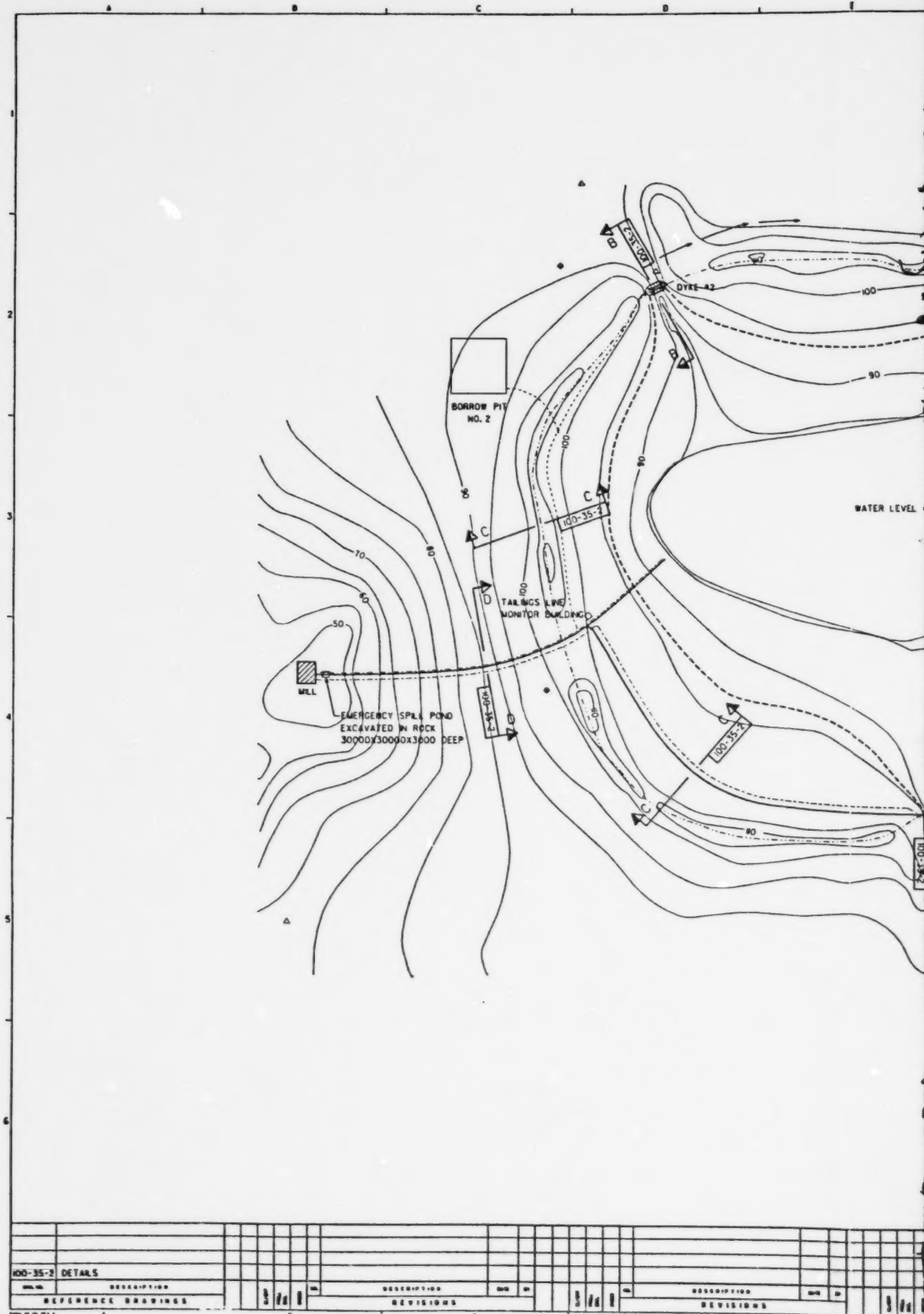
- exterior dyke slopes: 2.74:1
- interior dyke slopes on upstream and lateral embankments: 2:1
- interior dyke slopes on downstream embankment: 4:1
- average surface area of tailings: 42.6 ha
- catchment area: 49 ha
- average final tailings depth: 13 m
- runoff coefficient for precipitation: 0.9

#### BANCROFT

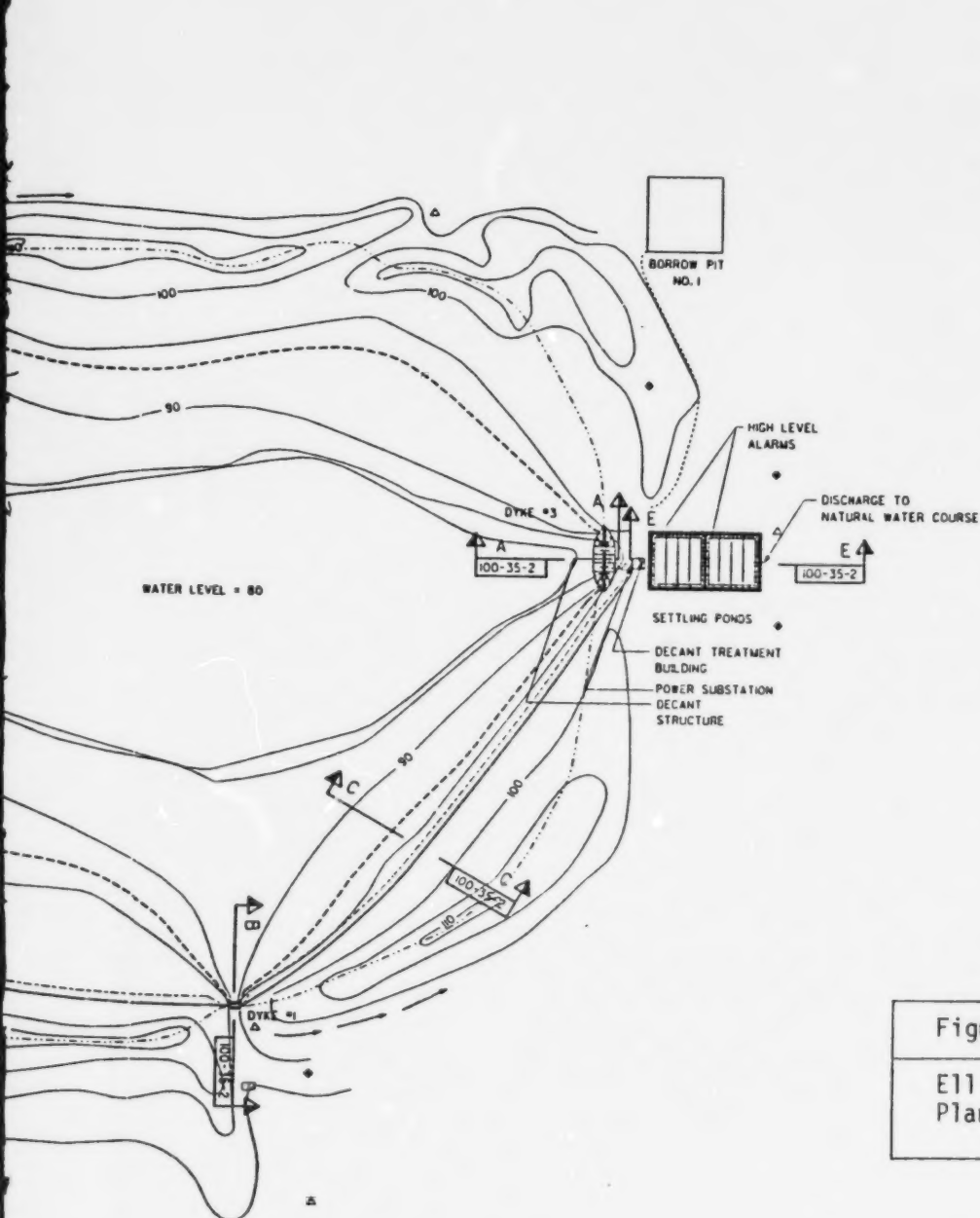
Bancroft tailings may be modelled by the following description. The tailings lie in swampy depressions of the area's low-hill Precambrian shield topography. They extend underwater where the tailings border lakes. Embankments are permeable piles of rock and gravel and their design and construction incorporate little engineering technology.

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| LEGEND                            |       |
|-----------------------------------|-------|
| CONTOUR                           | 100   |
| PERMANENT ROAD                    | —     |
| TEMPORARY CONSTRUCTION ROAD       | - - - |
| FINAL TAILINGS LEVEL              | ..... |
| TAILINGS PIPELINE                 | ..... |
| DRAINAGE BASIN                    | ..... |
| POWER SUPPLY LINE - 3 PHASE       | ..... |
| FRESH WATER DIVERSION DITCHES     | ..... |
| SURFACE WATER MONITORING STATIONS | Δ     |
| GROUNDWATER MONITORING PIEZOMETER | ◆     |

Figure C-1

Elliot Lake Model Impoundment - Plan View

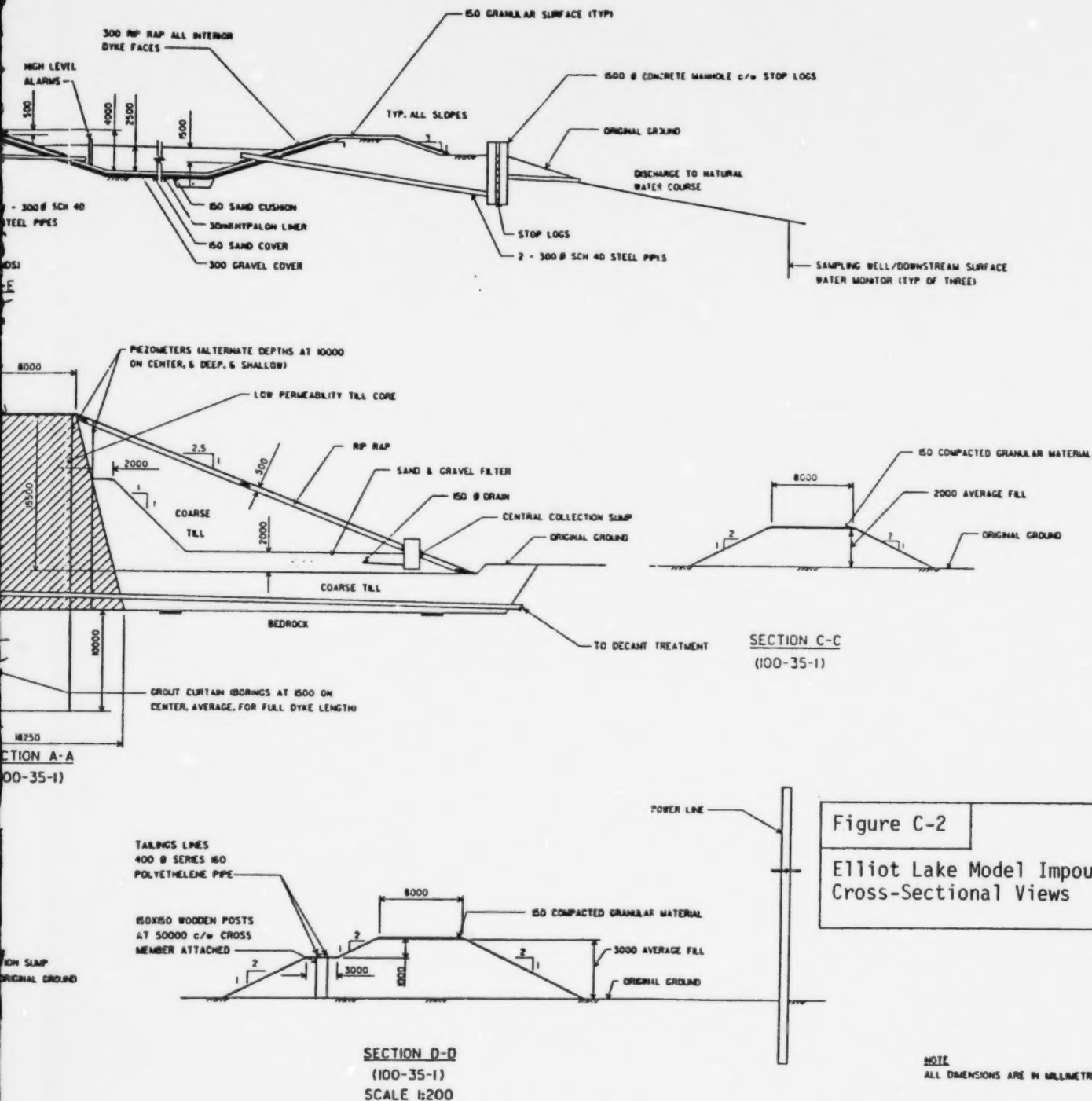
NOTE

- 1) ALL ELEVATIONS ARE IN METRES.
- 2) ASSUMED MILL ELEVATION 50.0
- 3) ALL DIMENSIONS ARE IN MILLIMETRES.
- 4) CLEARING REQUIRED ABOVE LAKE LEVEL TO FINAL TAILINGS LEVEL, DYKES, SETTLING PONDS, BORROW PITS.

0 100000 500000 1000000mm

| CIVIL LAYOUT |               |       |  | SUPPLY AND SERVICES CANADA |  |       |  | TITLE                             |  |           |  |
|--------------|---------------|-------|--|----------------------------|--|-------|--|-----------------------------------|--|-----------|--|
| Drawn        | 100000        | Scale |  | Drawn                      |  | Scale |  | Project No.                       |  | Sheet No. |  |
| Checked      | T. N. WALBURN | Date  |  | Checked                    |  | Date  |  | NATIONAL URANIUM TAILINGS PROGRAM |  |           |  |
| Reviewed     | P. A. FAME    | Date  |  | Reviewed                   |  | Date  |  | WASTE MANAGEMENT COST STUDY       |  |           |  |
| Approved     |               | Date  |  | Approved                   |  | Date  |  | MODEL A                           |  |           |  |
| Project      |               |       |  | Project                    |  |       |  | WASTE MANAGEMENT AREA             |  |           |  |
|              |               |       |  |                            |  |       |  | SITE PLAN                         |  |           |  |
| REVISIONS    |               |       |  | KILBORN                    |  |       |  | DRAWING NUMBER                    |  |           |  |
|              |               |       |  |                            |  |       |  | 100-35-1                          |  |           |  |
|              |               |       |  |                            |  |       |  | B                                 |  |           |  |





| NO. | DESCRIPTION               | DATE | BY   |
|-----|---------------------------|------|------|
| 1   | RELEASED FOR FINAL REPORT | 1970 | P.J. |
| 2   | RELEASED FOR DRAFT REPORT | 1970 | P.J. |
| 3   | DESCRIPTION               | DATE | BY   |

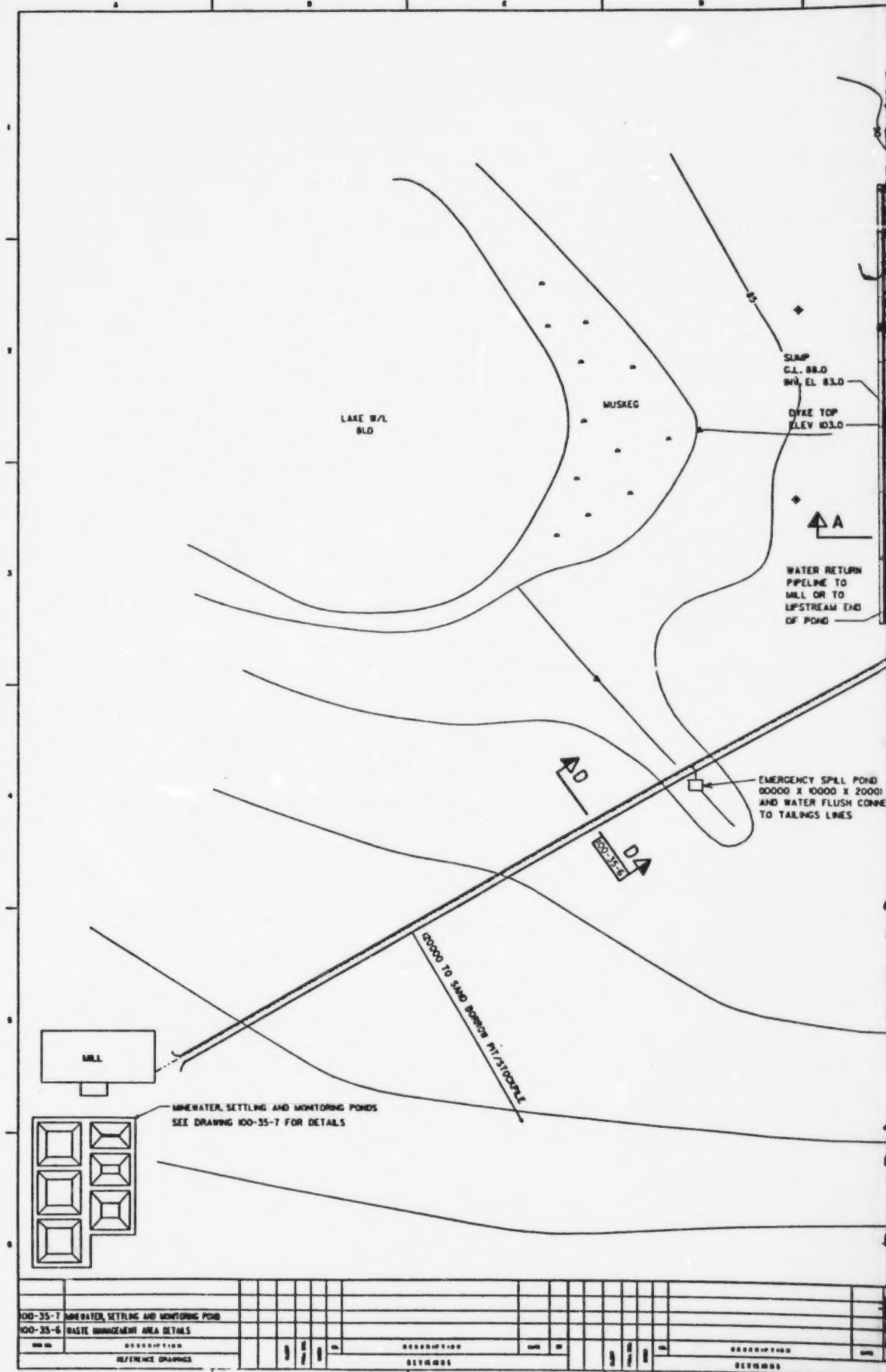
| NO. | DESCRIPTION  | DATE | BY   |
|-----|--------------|------|------|
| 1   | CIVIL LAYOUT | 1970 | P.J. |
| 2   | T.M. BALMAIN | 1970 | P.J. |
| 3   | P.A. FAYE    | 1970 | P.J. |

| NO. | DESCRIPTION                | DATE | BY   |
|-----|----------------------------|------|------|
| 1   | SUPPLY AND SERVICES CANADA | 1970 | P.J. |
| 2   | OTTAWA, CANADA             | 1970 | P.J. |

| NO. | DESCRIPTION                       | DATE | BY   |
|-----|-----------------------------------|------|------|
| 1   | NATIONAL URANIUM TAILINGS PROGRAM | 1970 | P.J. |
| 2   | WASTE MANAGEMENT COST STUDY       | 1970 | P.J. |
| 3   | MODEL & WASTE MANAGEMENT AREA     | 1970 | P.J. |

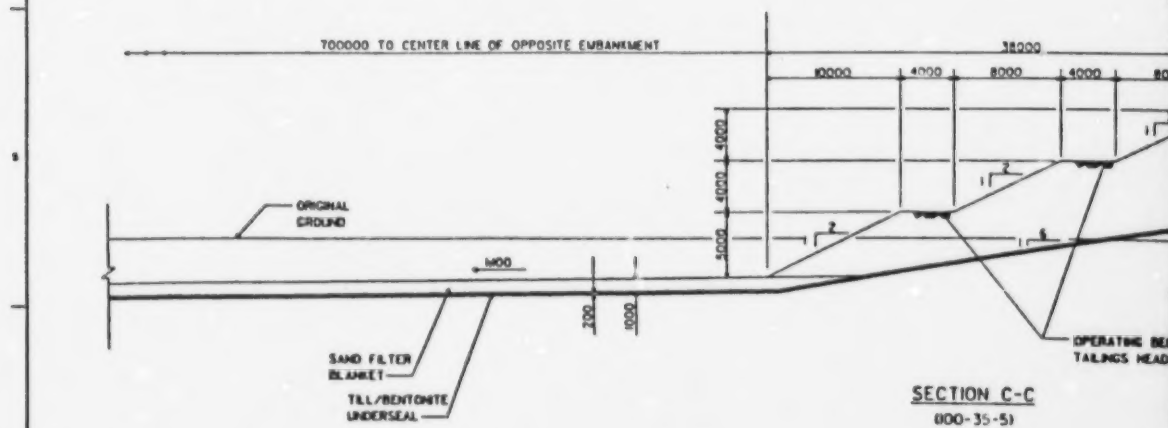
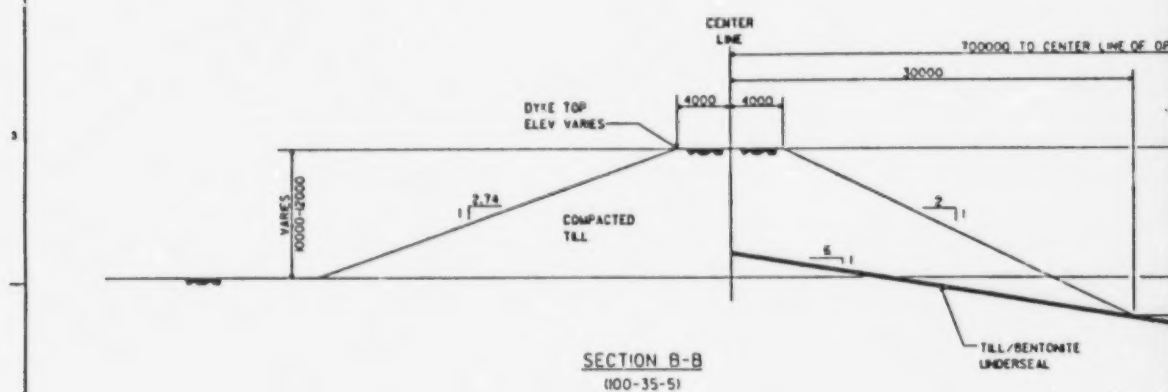
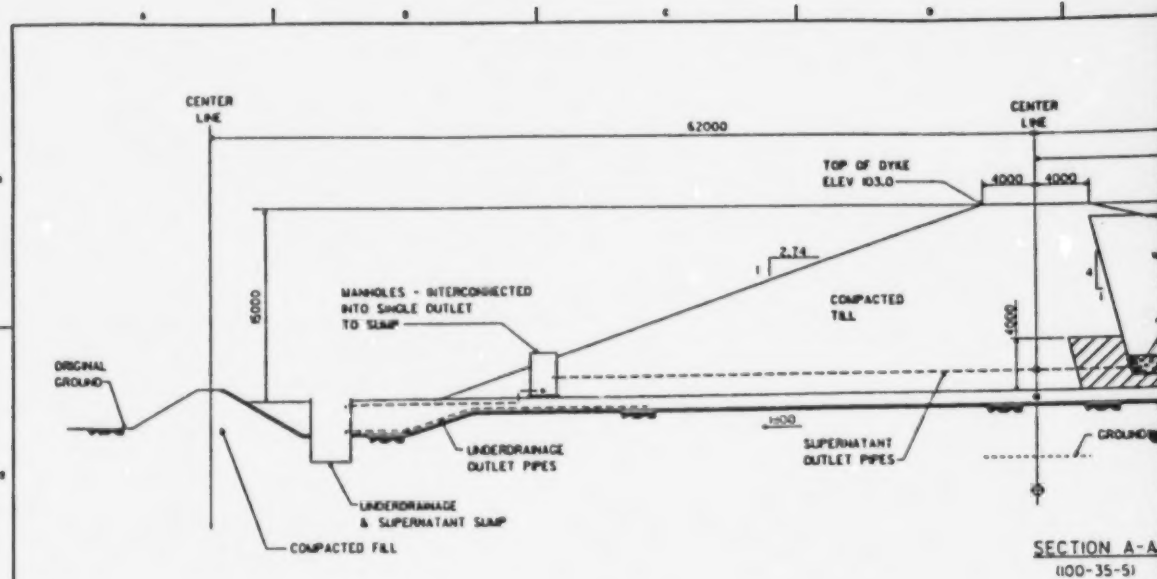
| NO. | DESCRIPTION | DATE | BY   |
|-----|-------------|------|------|
| 1   | 5279        | 1970 | P.J. |
| 2   | 100-35-2    | 1970 | P.J. |

KILBORN







[illegible]

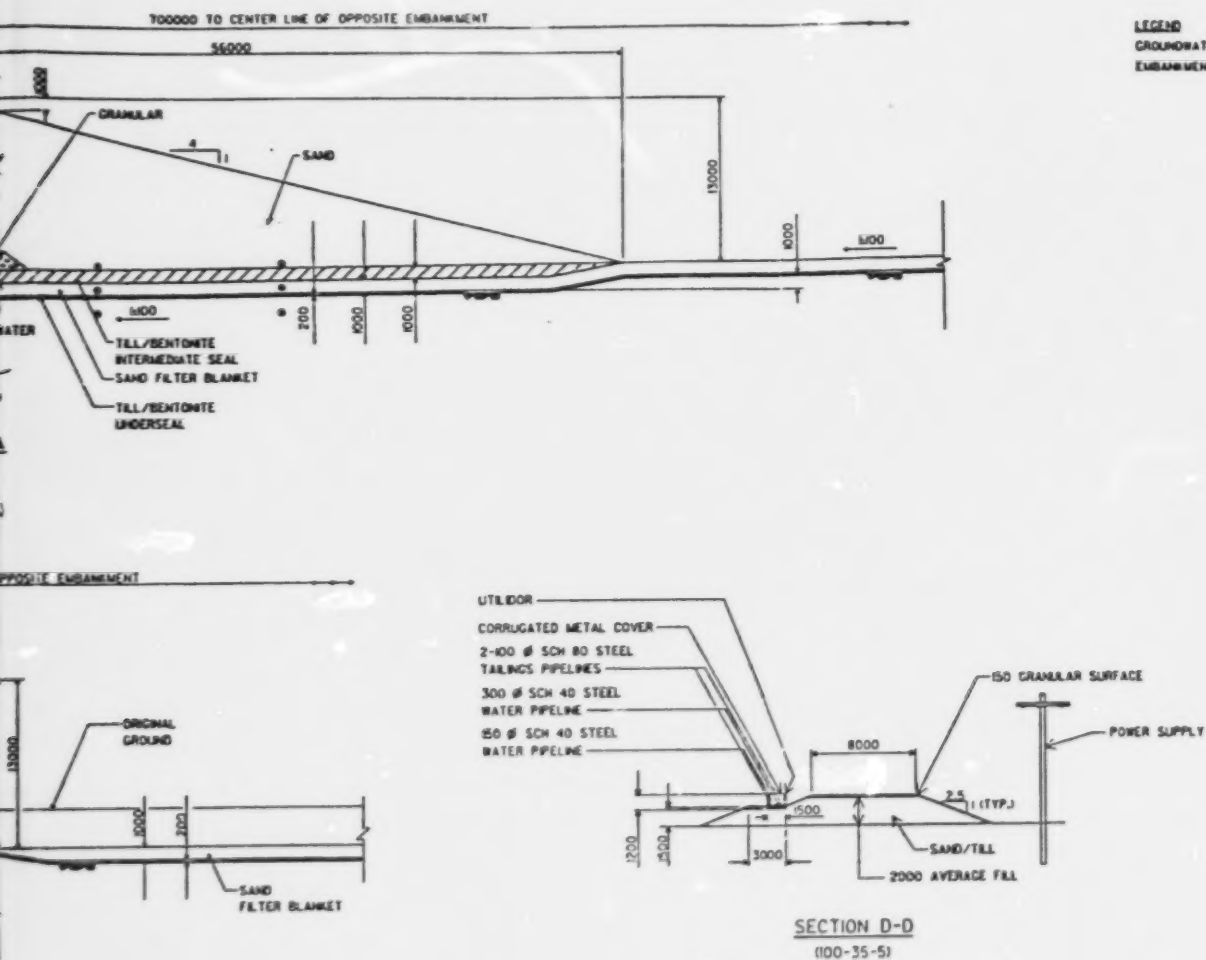
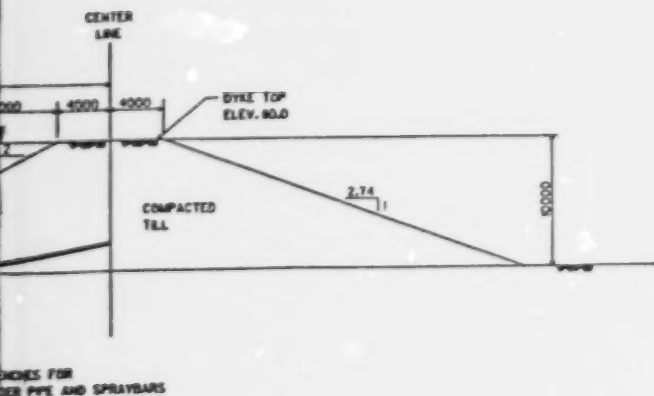


Figure C-4

Saskatchewan Model Impoundment - Cross-Sectional Views



|              |         |      |        |                                       |      |            |   |                                   |  |  |  |
|--------------|---------|------|--------|---------------------------------------|------|------------|---|-----------------------------------|--|--|--|
| CIVIL LAYOUT |         |      |        | WASTE SUPPLY AND SERVICES CANADA      |      |            |   | TITLE                             |  |  |  |
| DATE         | 6/30/80 | BY   | CHW    | PROJECT NO.                           | 5239 | DESIGN NO. | 8 | NATIONAL URANIUM TAILINGS PROGRAM |  |  |  |
| REVISION     | 1       | DATE | 7/1/80 | WASTE MANAGEMENT COST STUDY           |      |            |   | 000000000000                      |  |  |  |
| REVISION     | 2       | DATE | 7/1/80 | MODEL C WASTE MANAGEMENT AREA DETAILS |      |            |   | 100-35-6                          |  |  |  |
| KILBORN      |         |      |        | OTTAWA, CANADA                        |      |            |   | 8                                 |  |  |  |

APPENDIX D

TAILINGS SITE DESCRIPTIONS

● Tailings

1. Lorado, Gunnar, Beaverlodge
2. Rabbit Lake
3. Key Lake
4. Elliot Lake
5. Bancroft

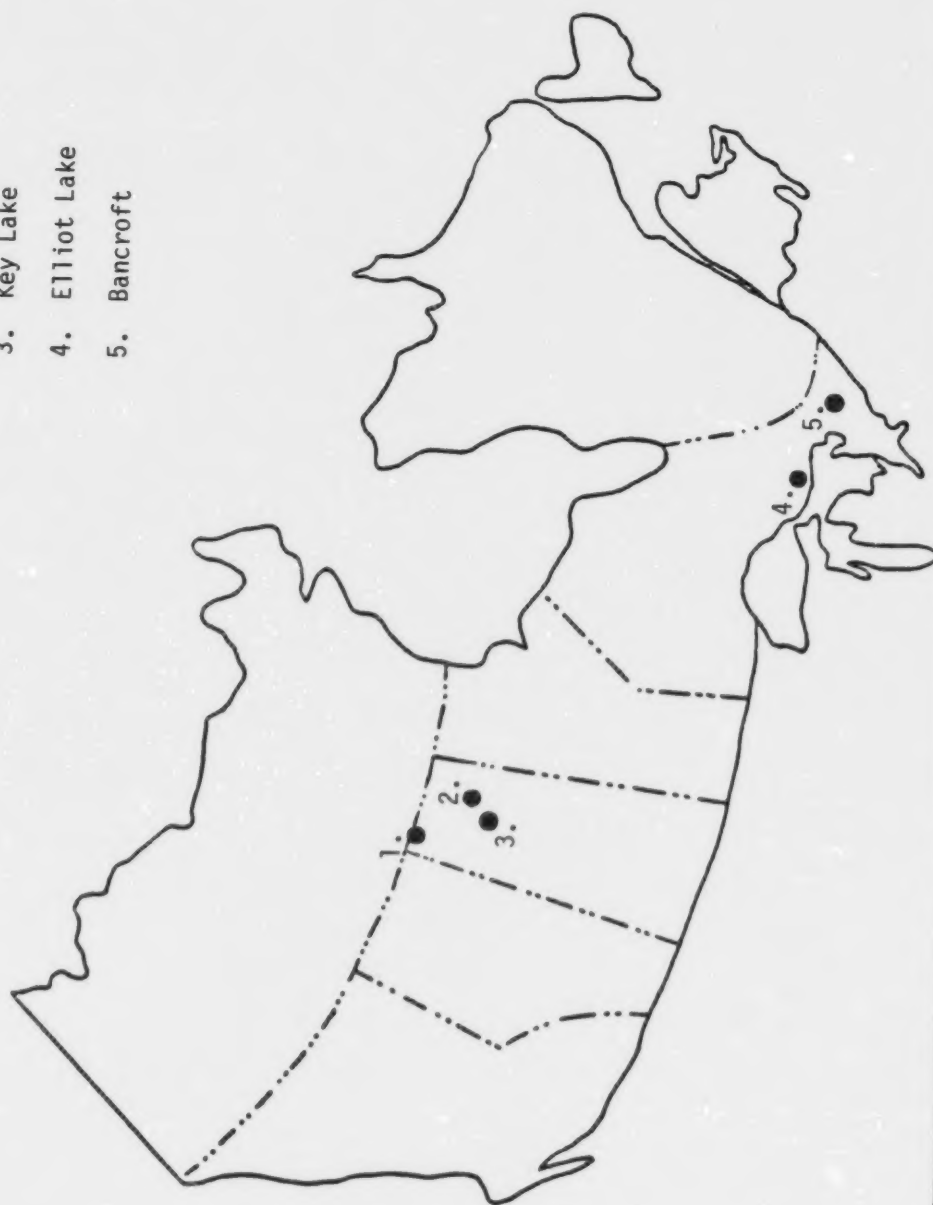


Figure D-1. Location of uranium tailings sites in Canada (adapted from (D-1))

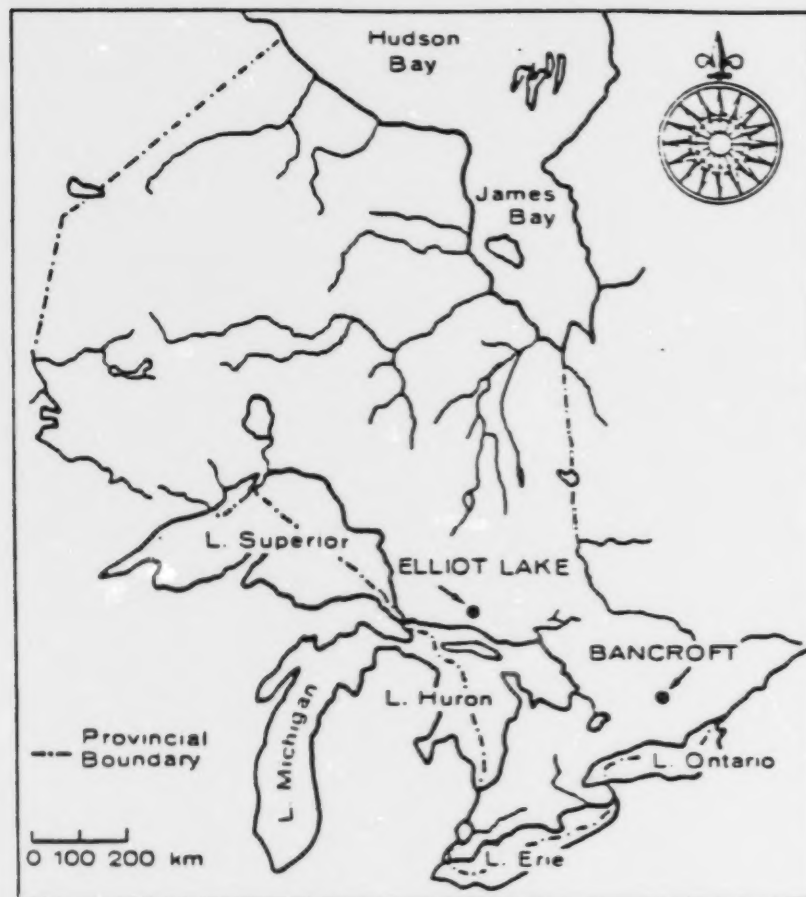


Figure D-2. Location of Elliot Lake and Bancroft, Ontario (D-2)



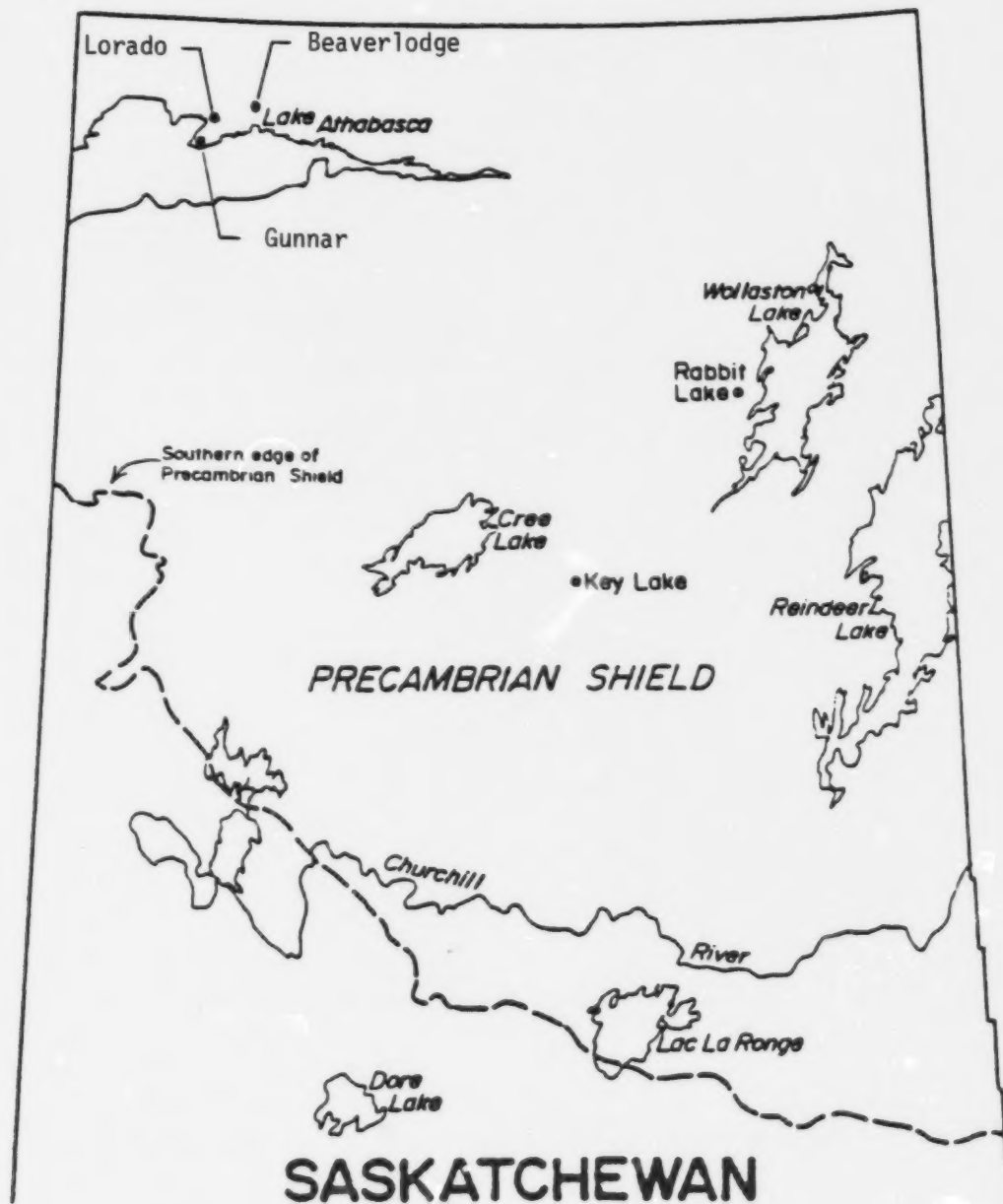
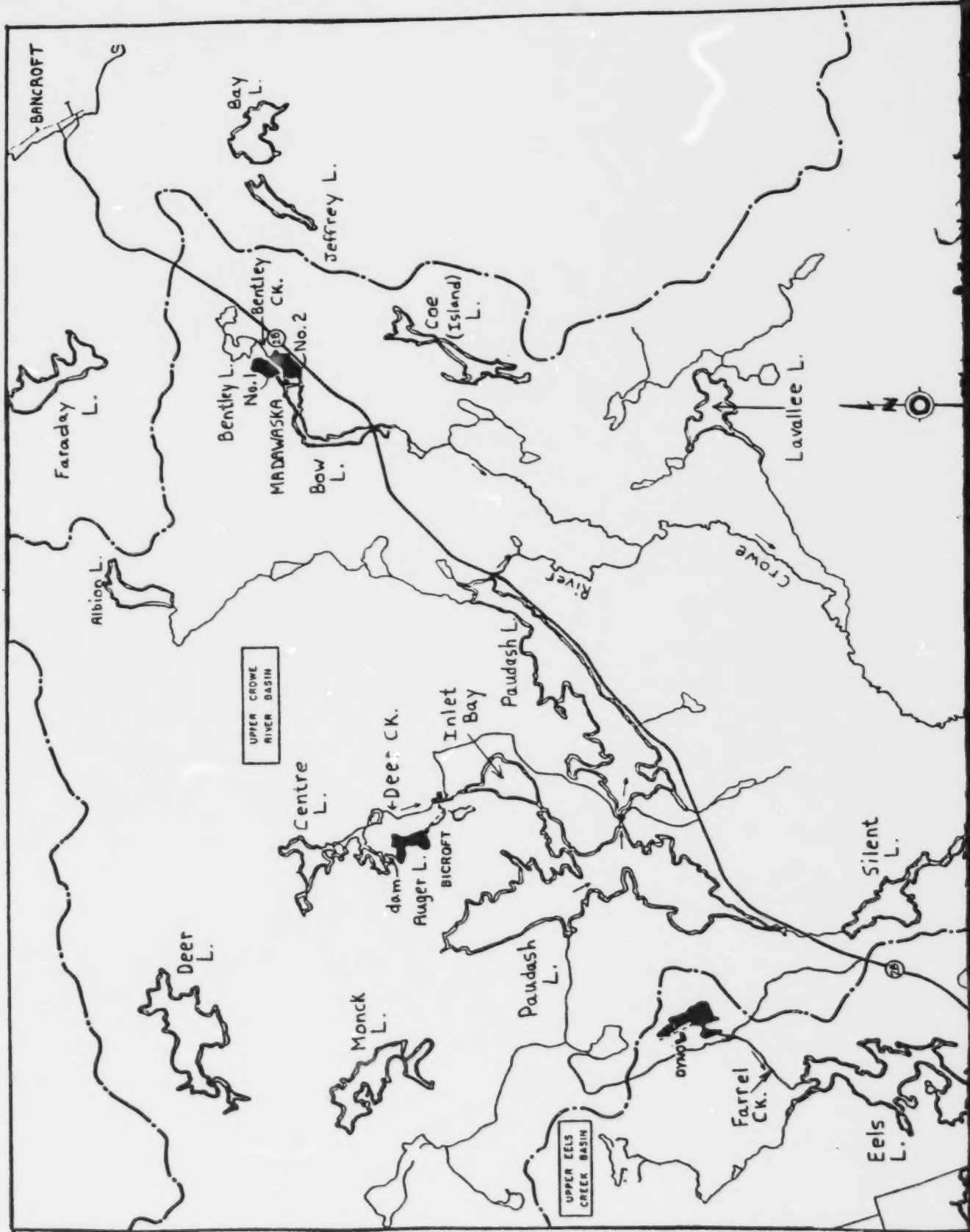


Figure D-3. Location of Saskatchewan uranium tailings sites  
(adapted from (D-3))



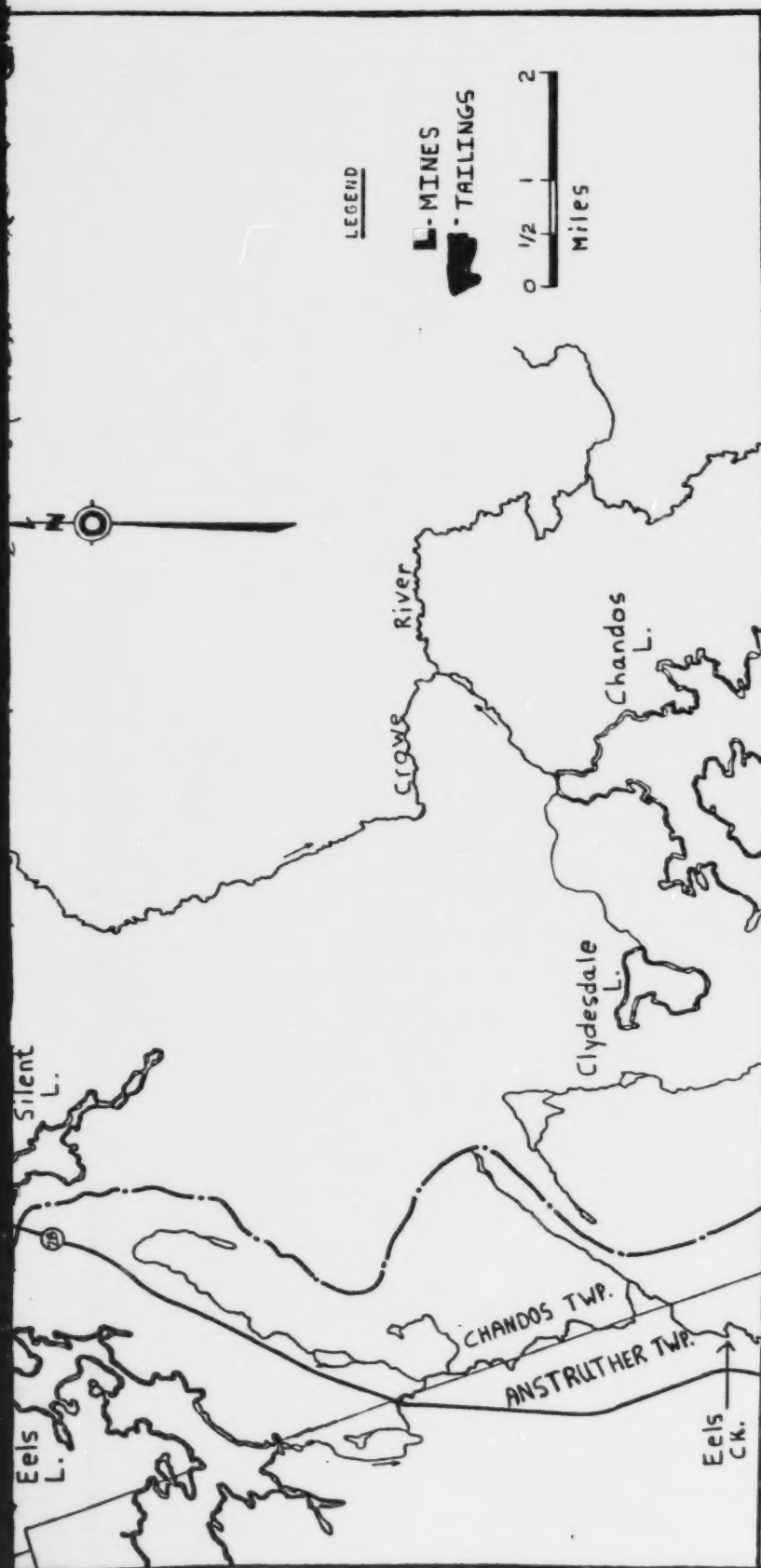
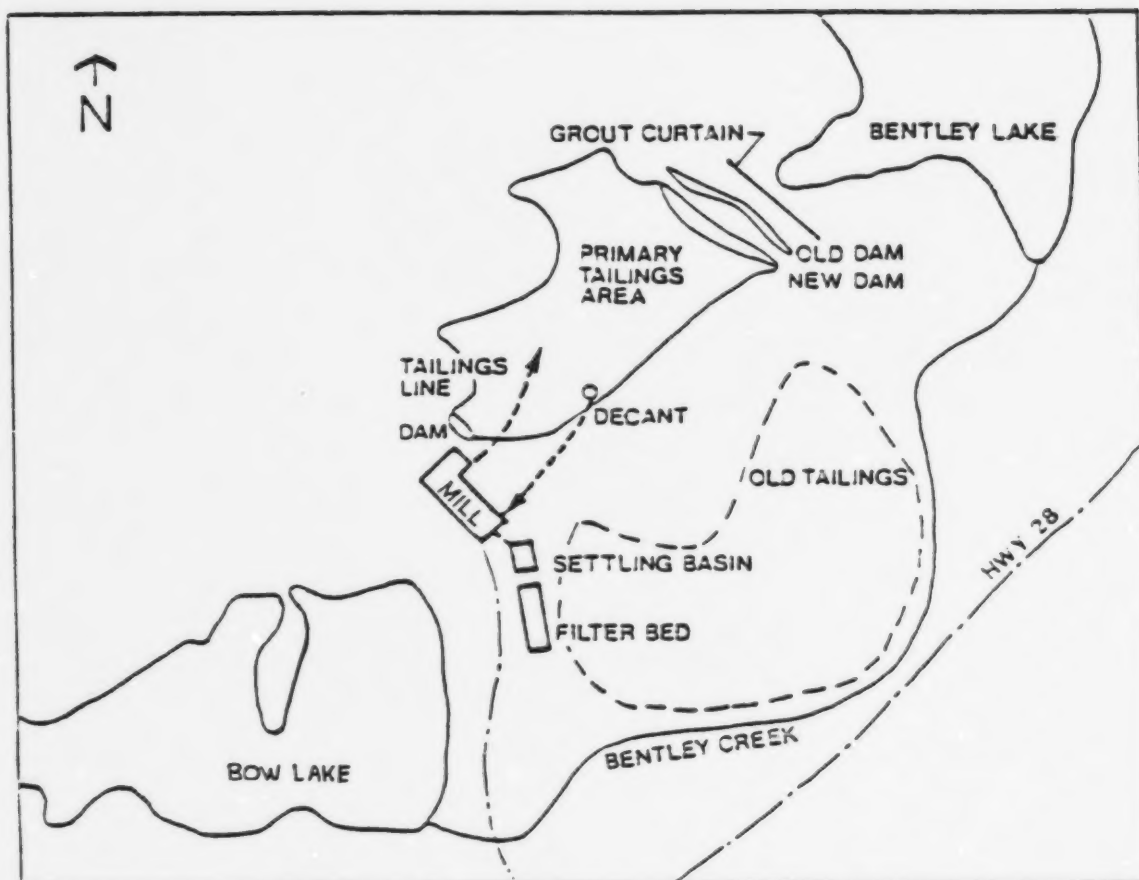


FIGURE D-4

Location of Bancroft  
tailings sites



0 1000 2000

Scale in feet

Figure D-5. Madawaska site: tailings management system (D-4)

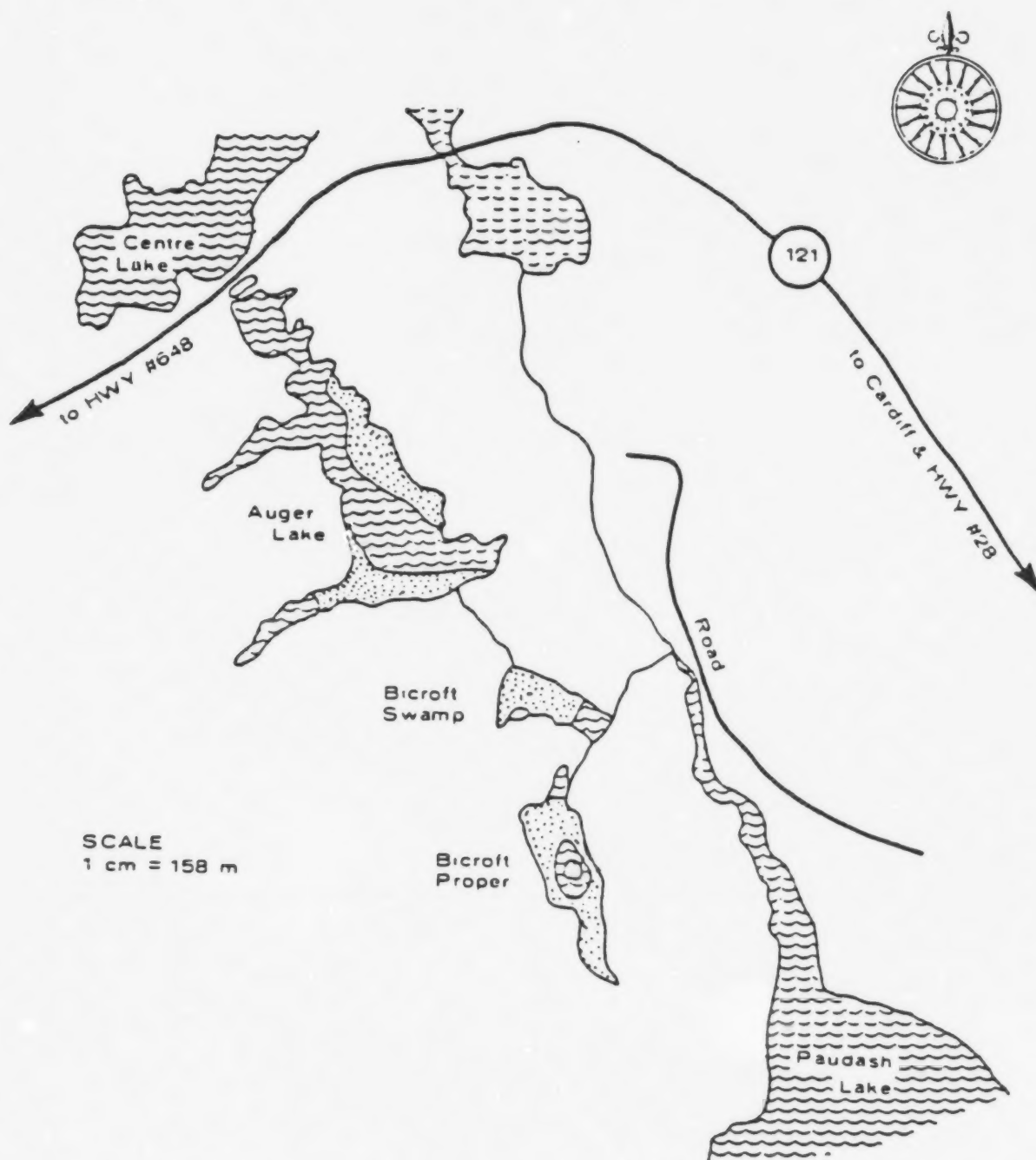


Figure D-6. Bicroft tailings site (adapted from (D-2))



Scale: 1 cm = 39.1 m  
Area: 0.027 km<sup>2</sup>

LEGEND

-  bare tailings
-  moss cover
-  trees
-  shrubs
-  sedge colonies only
-  water
-  surface drainage
-  dam

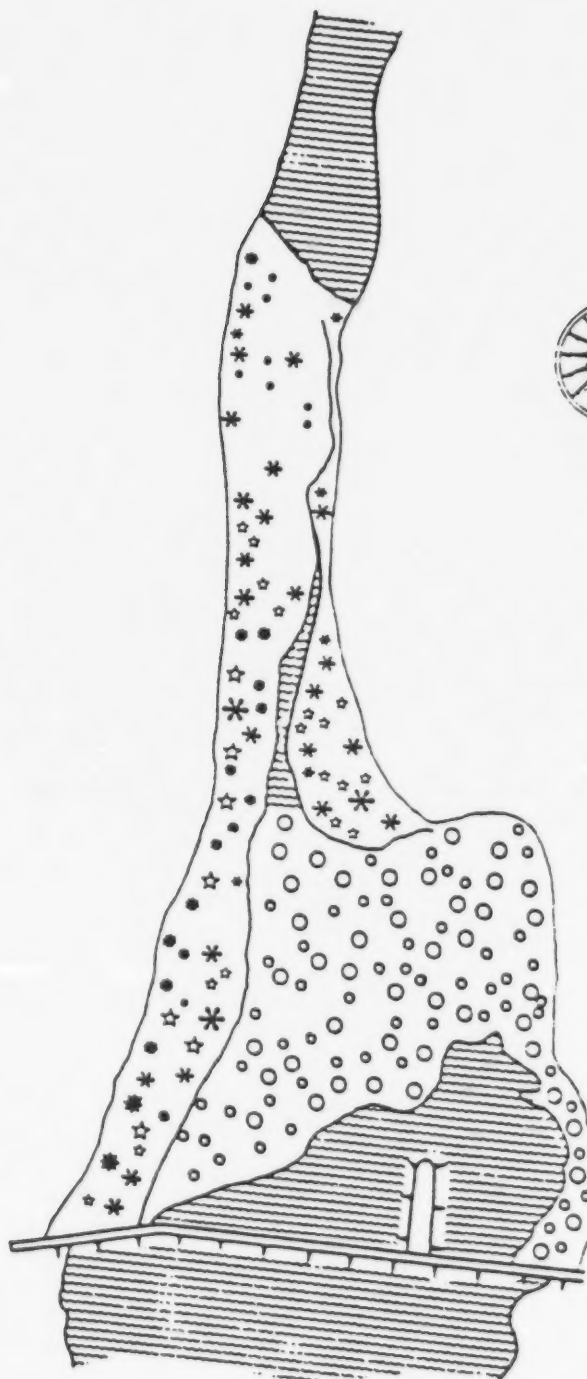


Figure D-7. Dyno tailings site (D-2)

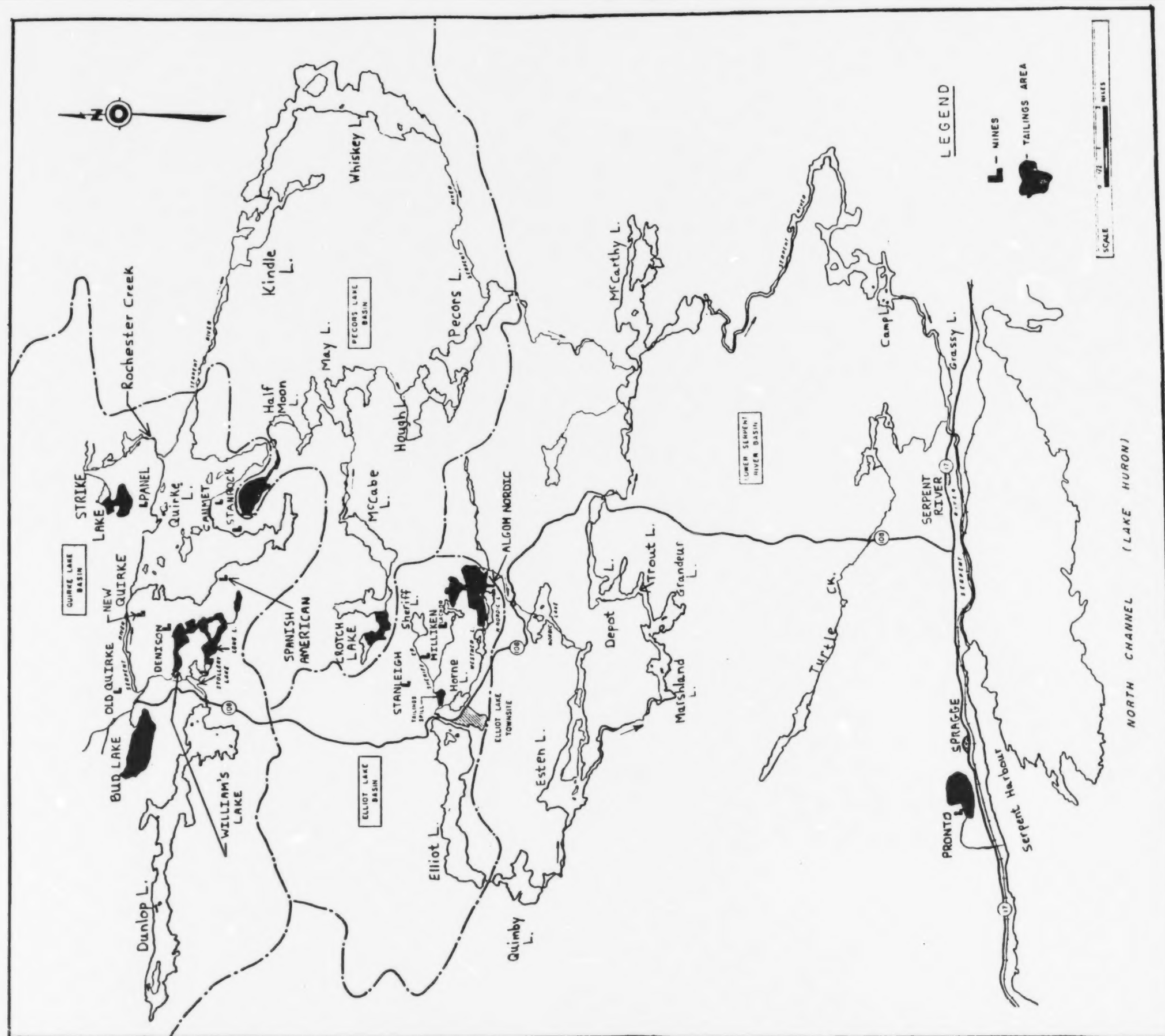


FIGURE D-8

Location of Elliot Lake  
tailings sites

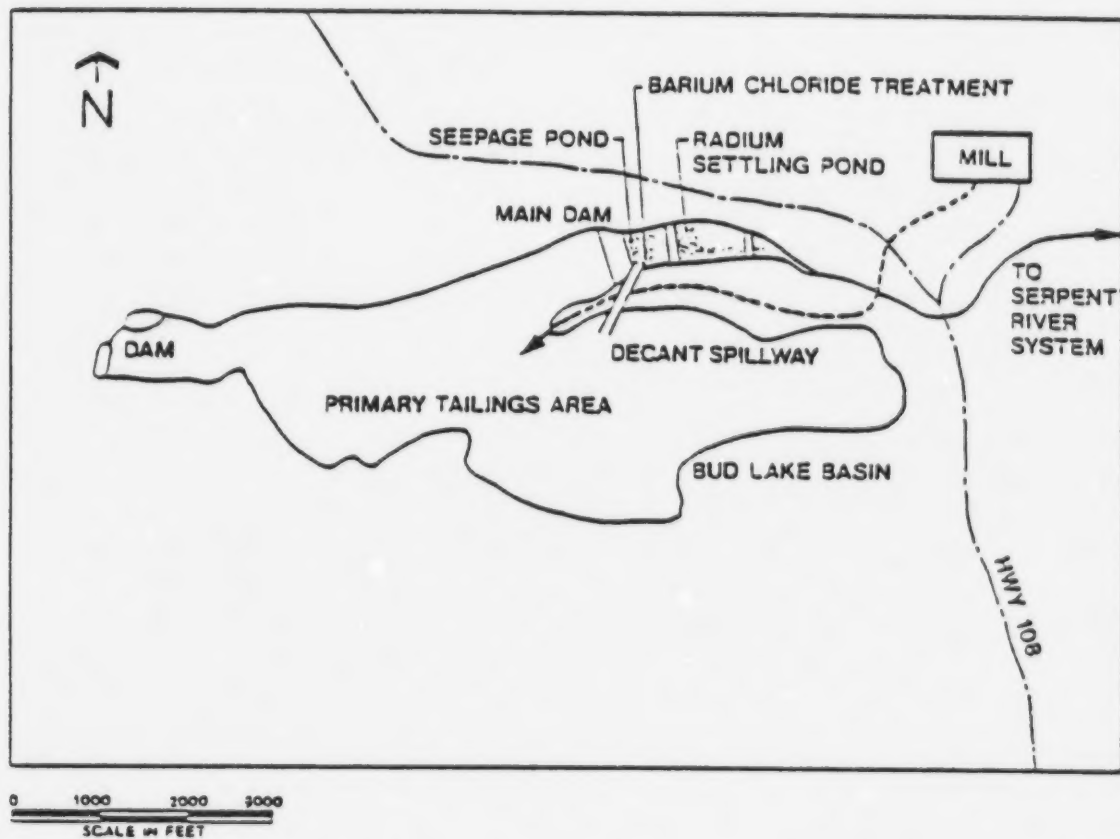


Figure D-9. Quirke site: tailings management system (D-4)

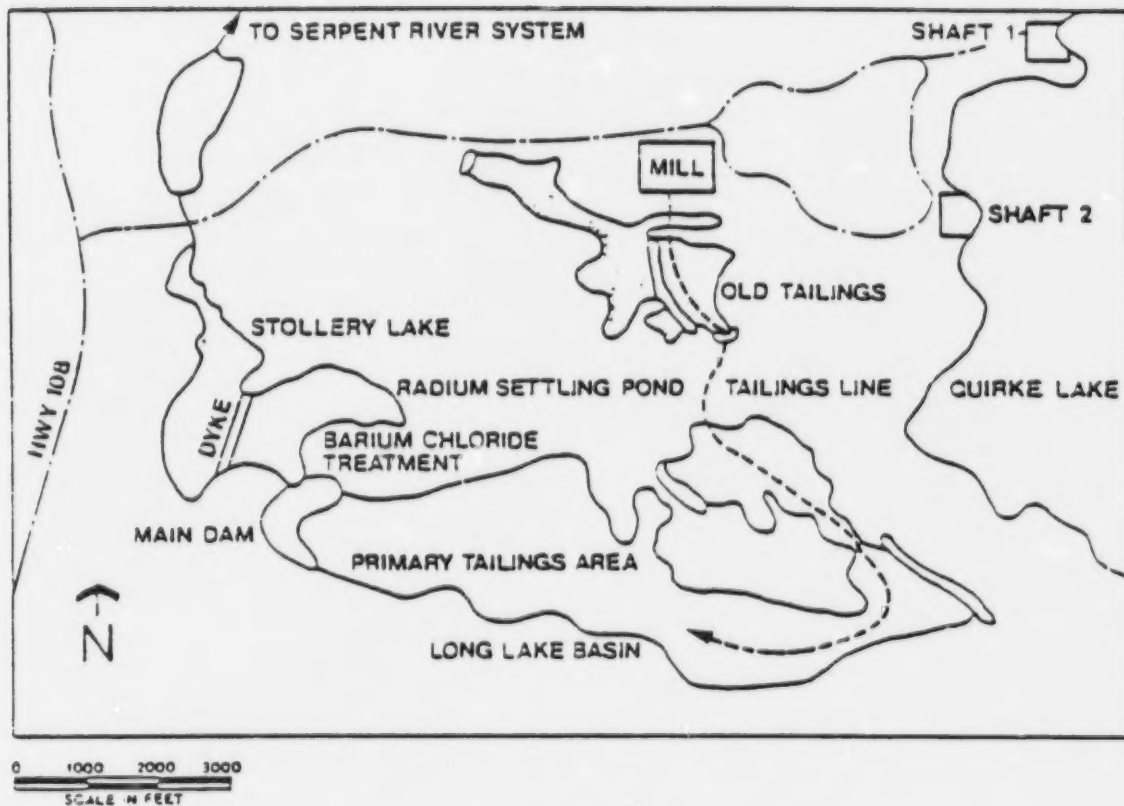


Figure D-10. Long Lake site: tailings management system (D-4)

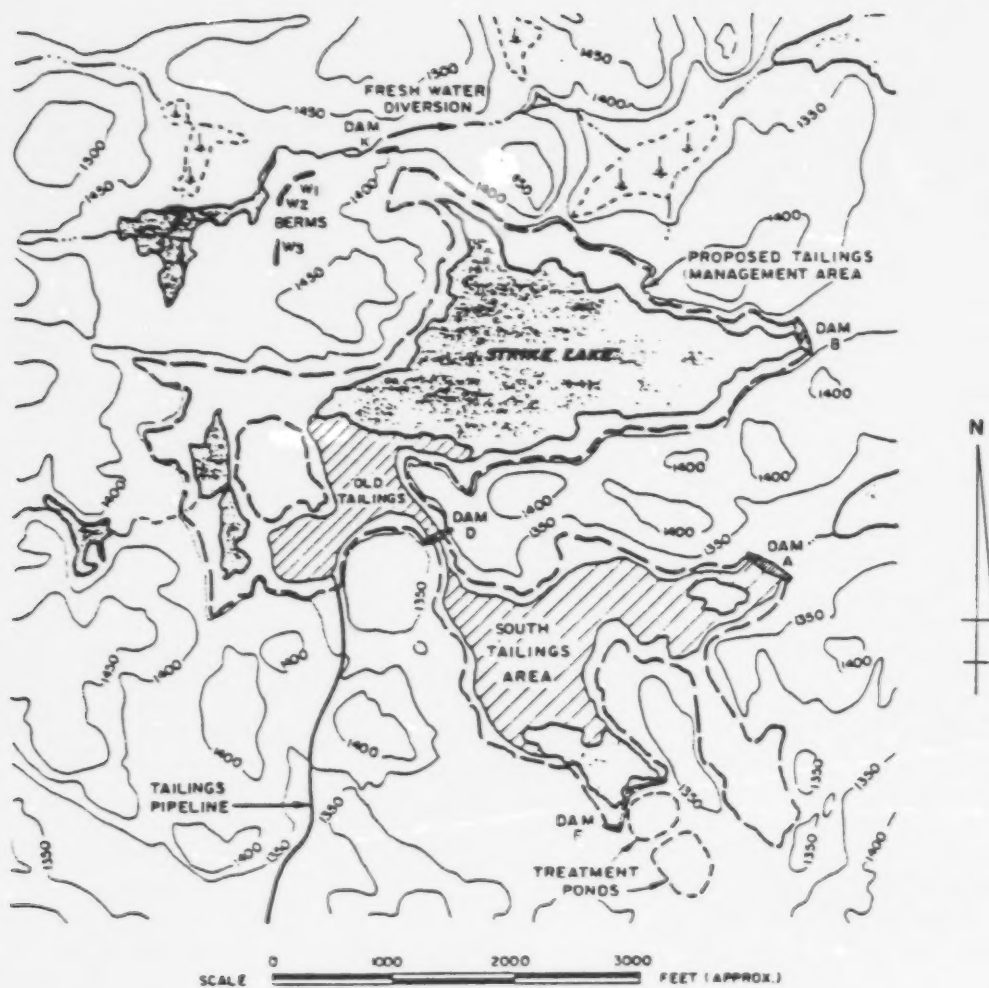
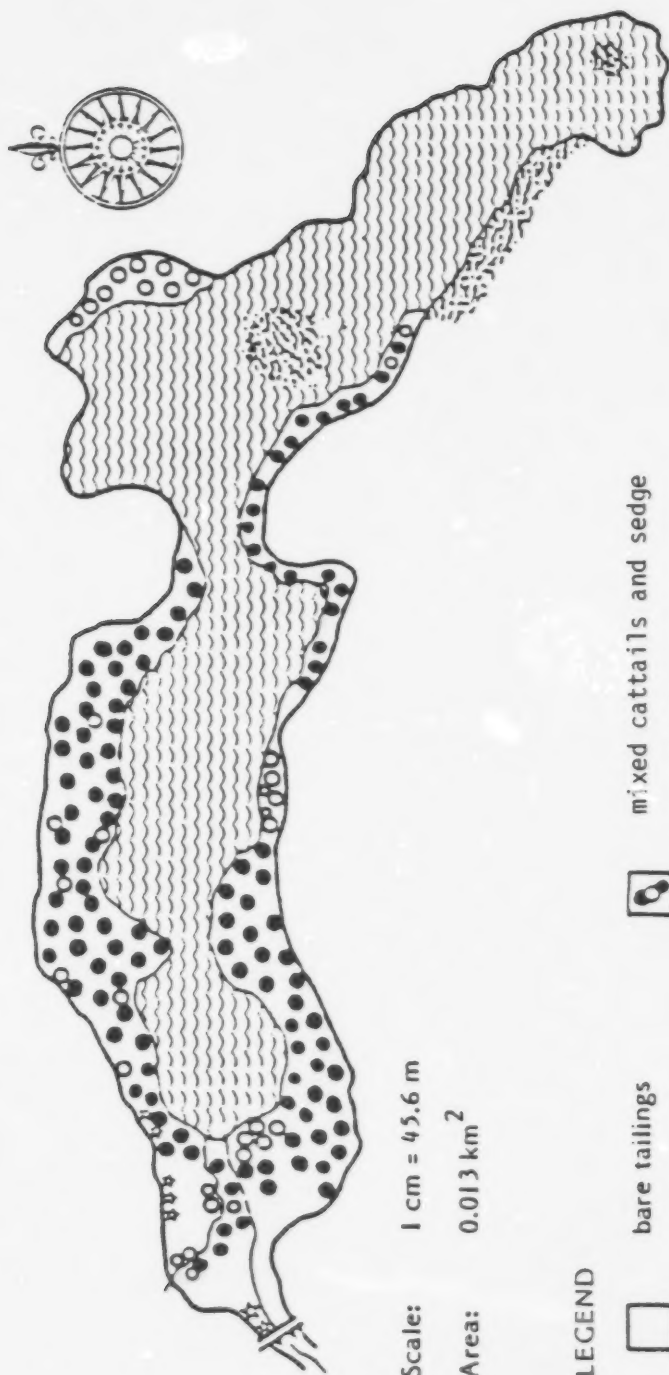


Figure D-11. Panel tailings site (D-5)





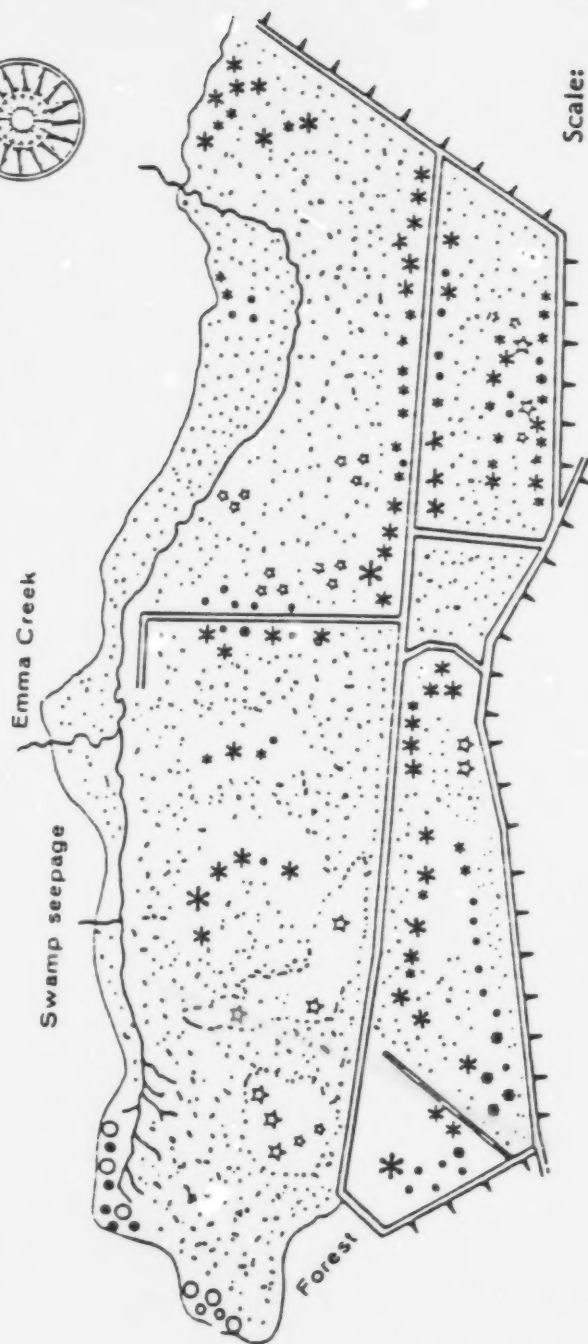
# LEGEND

|                                                                                       |                       |                                                                                       |                          |
|---------------------------------------------------------------------------------------|-----------------------|---------------------------------------------------------------------------------------|--------------------------|
|    | bare tailings         |    | mixed cattails and sedge |
|  | moss cover            |  | rock and gravel          |
|  | cattail colonies only |  | water                    |
|  | sedge colonies only   |  | dam                      |

Figure D-12. Panel site - Dam A tailings (D-2)

# LEGEND

|                                                                                     |                     |                                                                                     |        |                                                                                     |                          |                                                                                   |                  |
|-------------------------------------------------------------------------------------|---------------------|-------------------------------------------------------------------------------------|--------|-------------------------------------------------------------------------------------|--------------------------|-----------------------------------------------------------------------------------|------------------|
|  | bare tailings       |  | trees  |  | sedge colonies only      |  | road             |
|  | revegetated (alive) |  | shrubs |  | mixed cattails and sedge |  | surface drainage |
|  | moss cover          |                                                                                     |        |                                                                                     |                          |  | dam              |

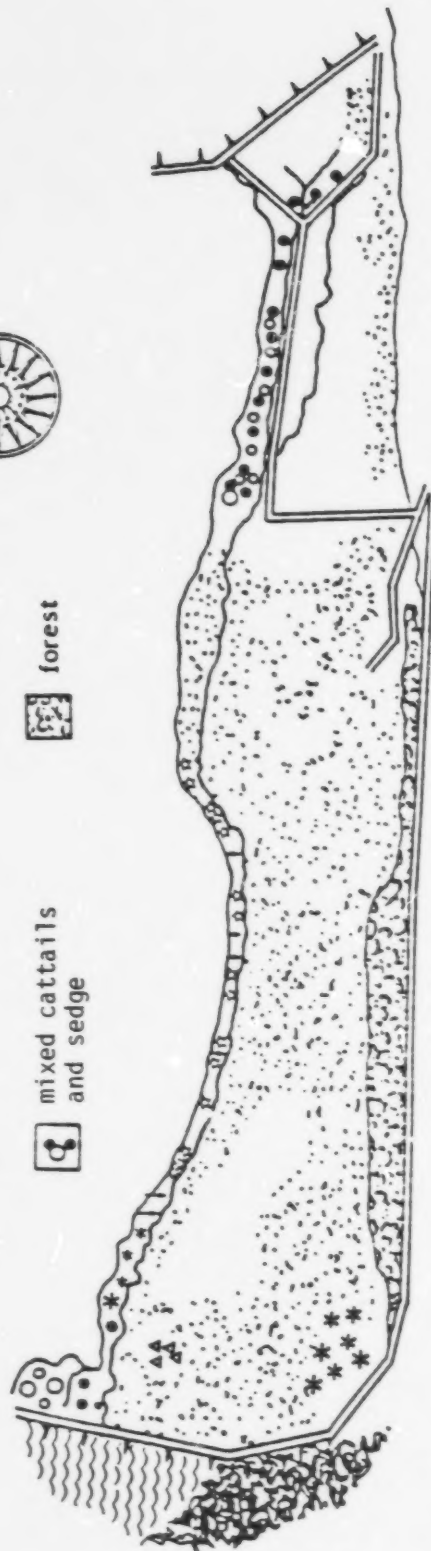


Scale: 1 cm = 93.2 m  
Area: 0.85 km<sup>2</sup>

Figure D-13. Nordic site - Main tailings (D-2)

# LEGEND

|                                                                                     |                     |                                                                                     |                          |                                                                                   |                  |
|-------------------------------------------------------------------------------------|---------------------|-------------------------------------------------------------------------------------|--------------------------|-----------------------------------------------------------------------------------|------------------|
|  | bare tailings       |  | trees                    |  | rock and gravel  |
|  | revegetated (alive) |  | tree seedlings           |  | water            |
|  | revegetated (dead)  |  | shrubs                   |  | road             |
|  | moss cover          |  | cattail colonies only    |  | surface drainage |
|                                                                                     |                     |  | sedge colonies only      |  | dam              |
|                                                                                     |                     |  | mixed cattails and sedge |  | forest           |



Scale: 1 cm = 55.1 m  
Area: 0.16 km<sup>2</sup>

Figure D-14. Nordic site - West Arm tailings (D-2)

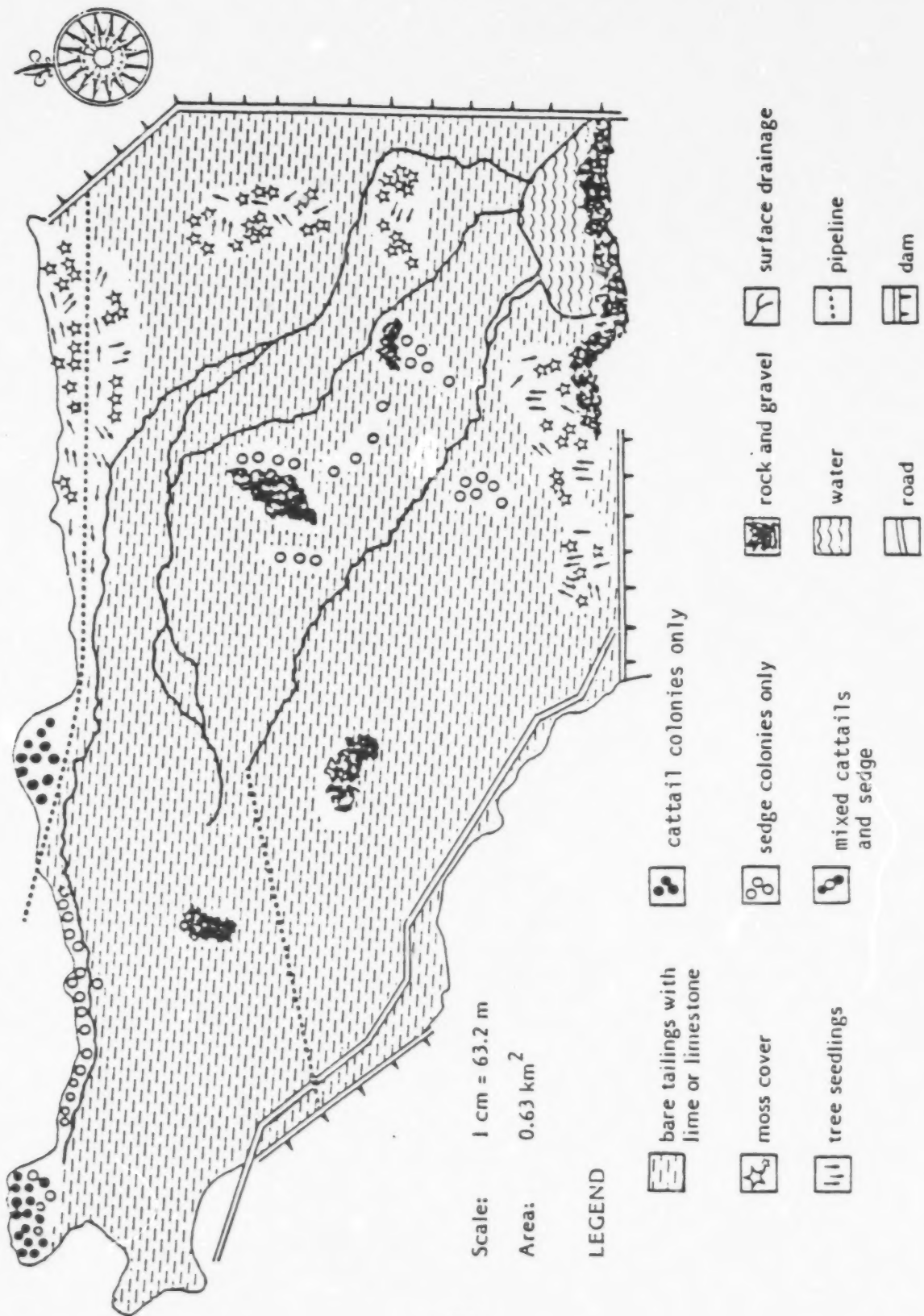


Figure D-15. Stanrock site - Main tailings (D-2)

# LEGEND

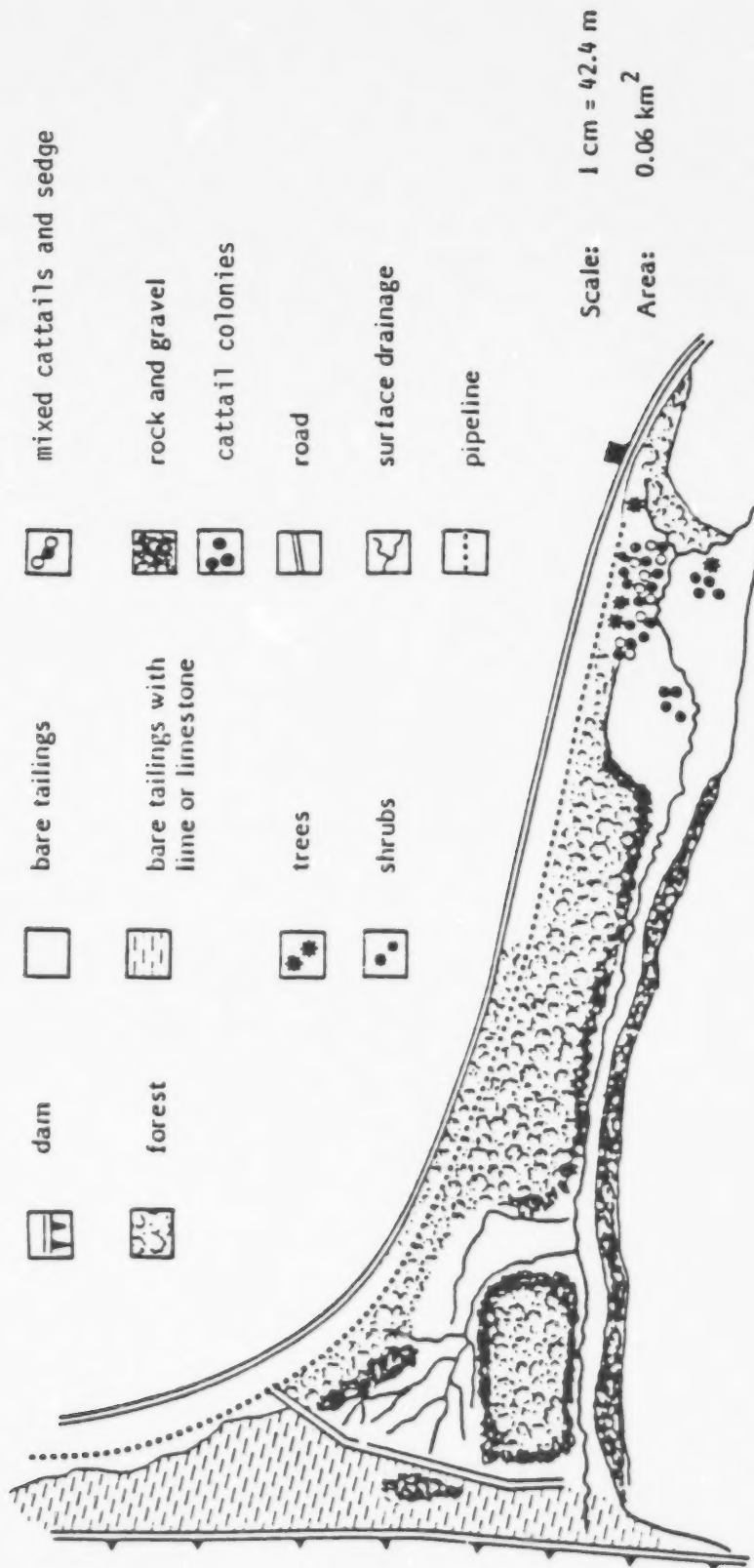
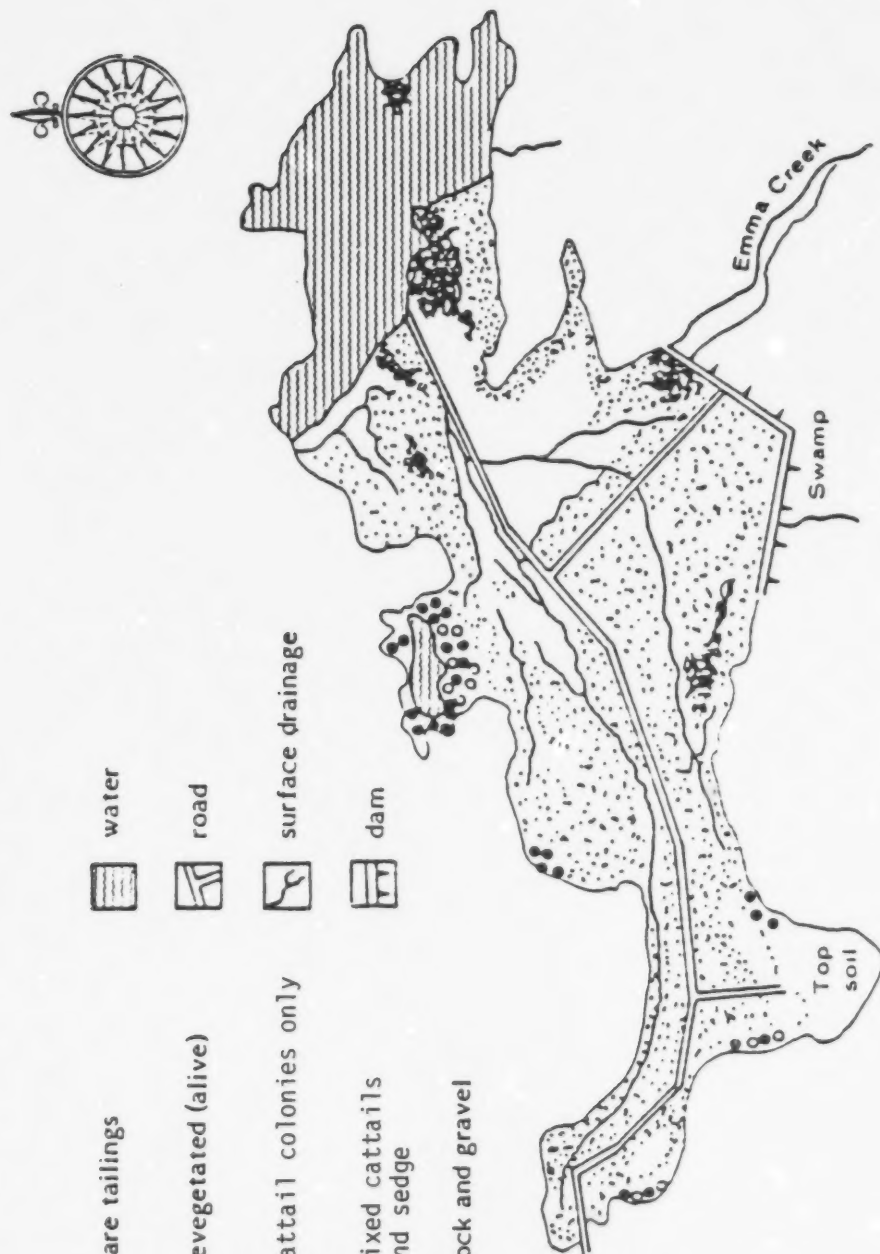


Figure D-16. Stanrock site - Dam A tailings (D-2)



# LEGEND

|                                                                                     |                          |                                                                                     |                  |
|-------------------------------------------------------------------------------------|--------------------------|-------------------------------------------------------------------------------------|------------------|
|  | bare tailings            |  | water            |
|  | revegetated (alive)      |  | road             |
|  | cattail colonies only    |  | surface drainage |
|  | mixed cattails and sedge |  | dam              |
|  | rock and gravel          |                                                                                     |                  |

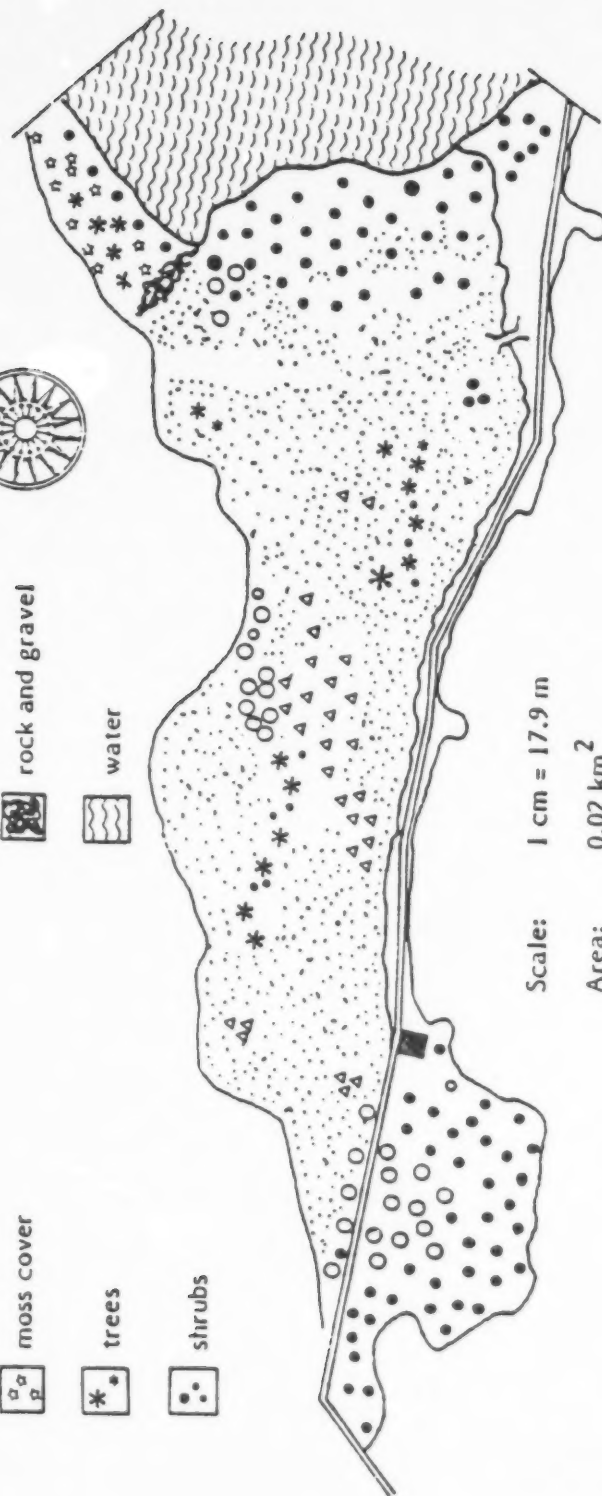


Scale: 1 cm = 73.1 m  
Area: 0.24 km<sup>2</sup>

Figure D-17. Lacnor tailings site (D-2)

# LEGEND

- |                                                                                     |                     |                                                                                     |                          |                                                                                   |      |
|-------------------------------------------------------------------------------------|---------------------|-------------------------------------------------------------------------------------|--------------------------|-----------------------------------------------------------------------------------|------|
|  | bare tailings       |  | cattail colonies only    |  | road |
|  | revegetated (alive) |  | sedge colonies only      |                                                                                   |      |
|  | revegetated (dead)  |  | mixed cattails and sedge |                                                                                   |      |
|  | moss cover          |  | rock and gravel          |                                                                                   |      |
|  | trees               |  | water                    |                                                                                   |      |
|  | shrubs              |                                                                                     |                          |                                                                                   |      |



Scale: 1 cm = 17.9 m

Area: 0.02 km<sup>2</sup>

Figure D-18. Lower Williams tailings site (D-2)

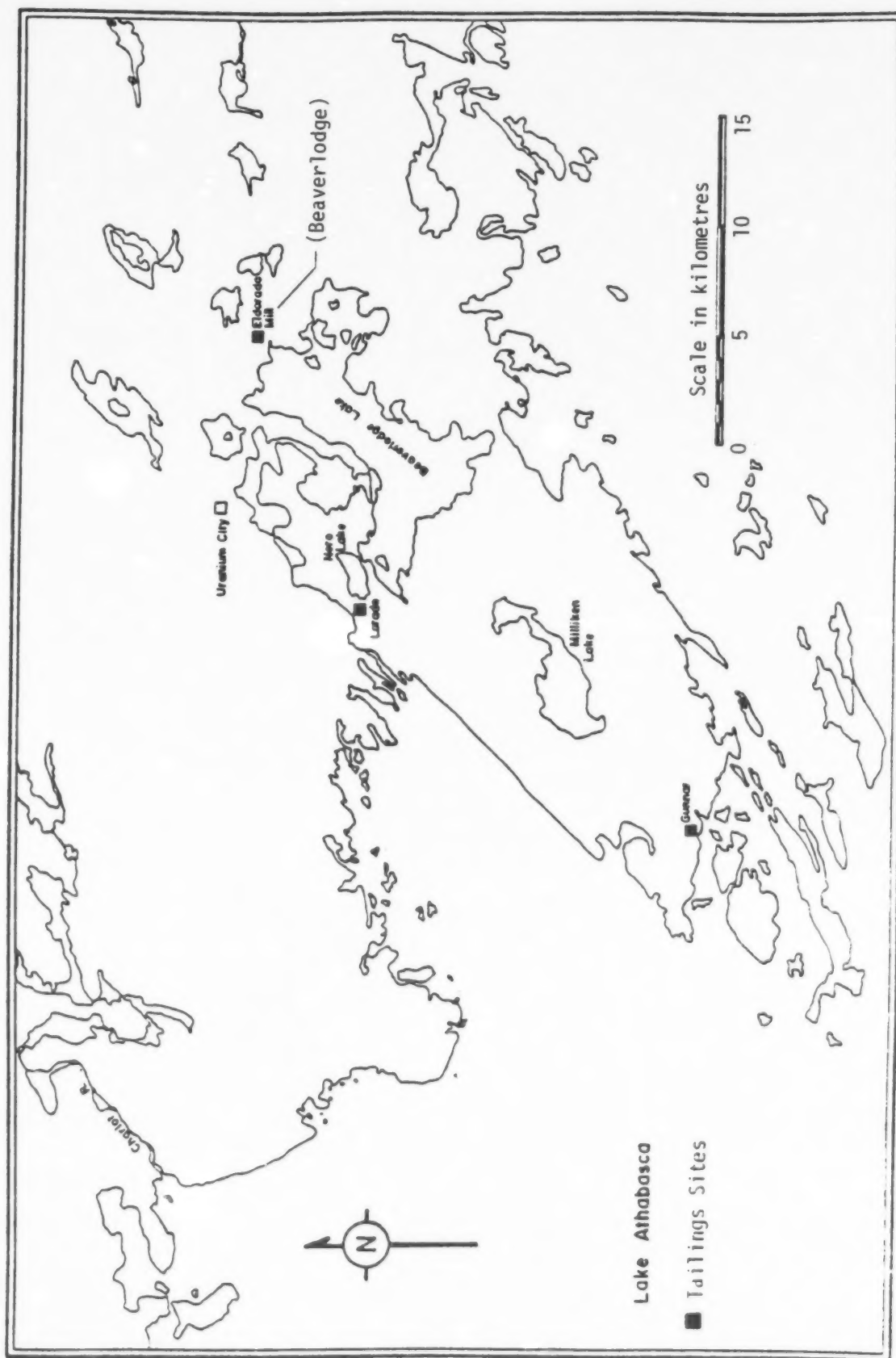


Figure D-19. Location of Lorado, Gunnar and Beaverlodge tailings sites (adapted from (D-6))

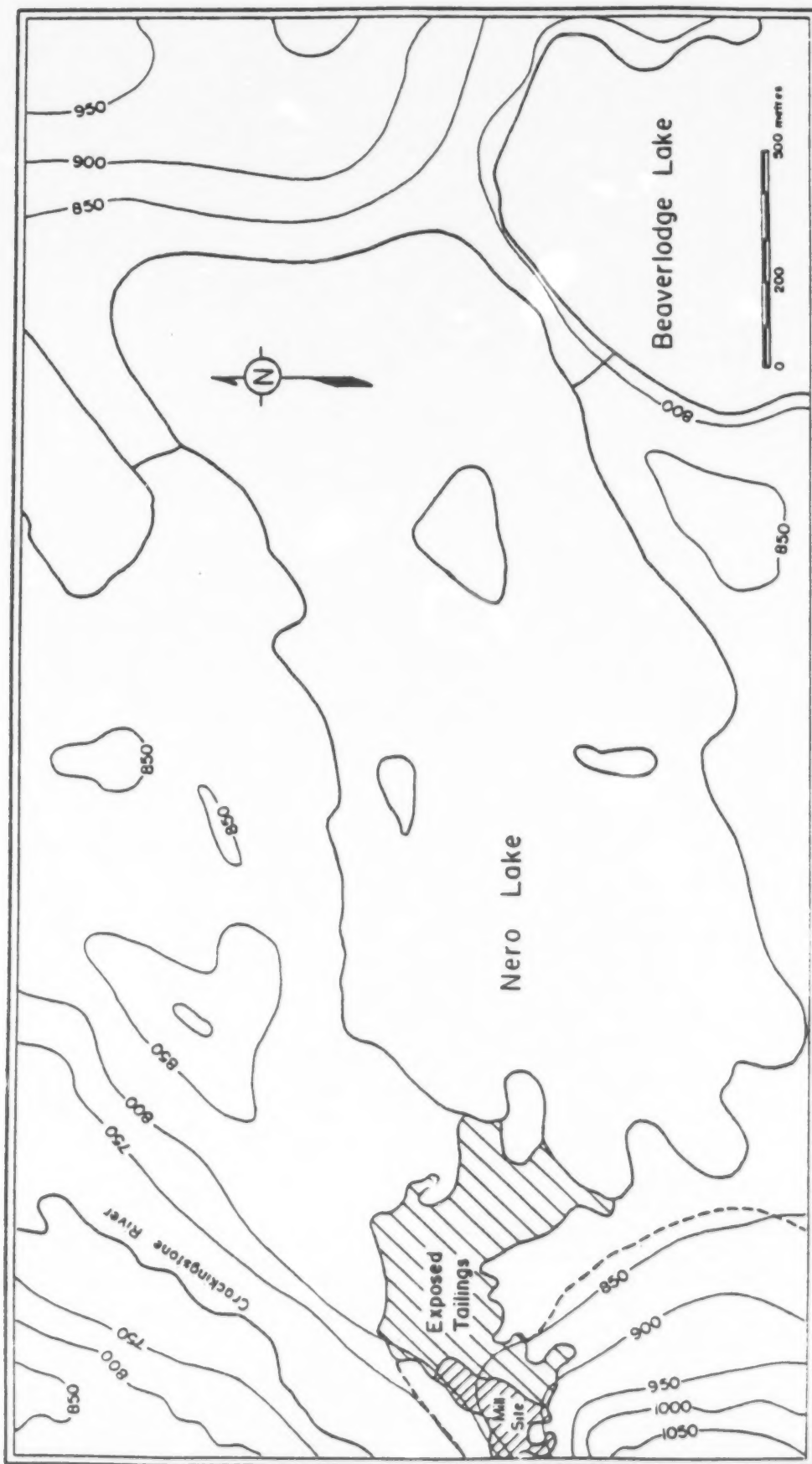


Figure D-20. Lorado tailings site (D-6)

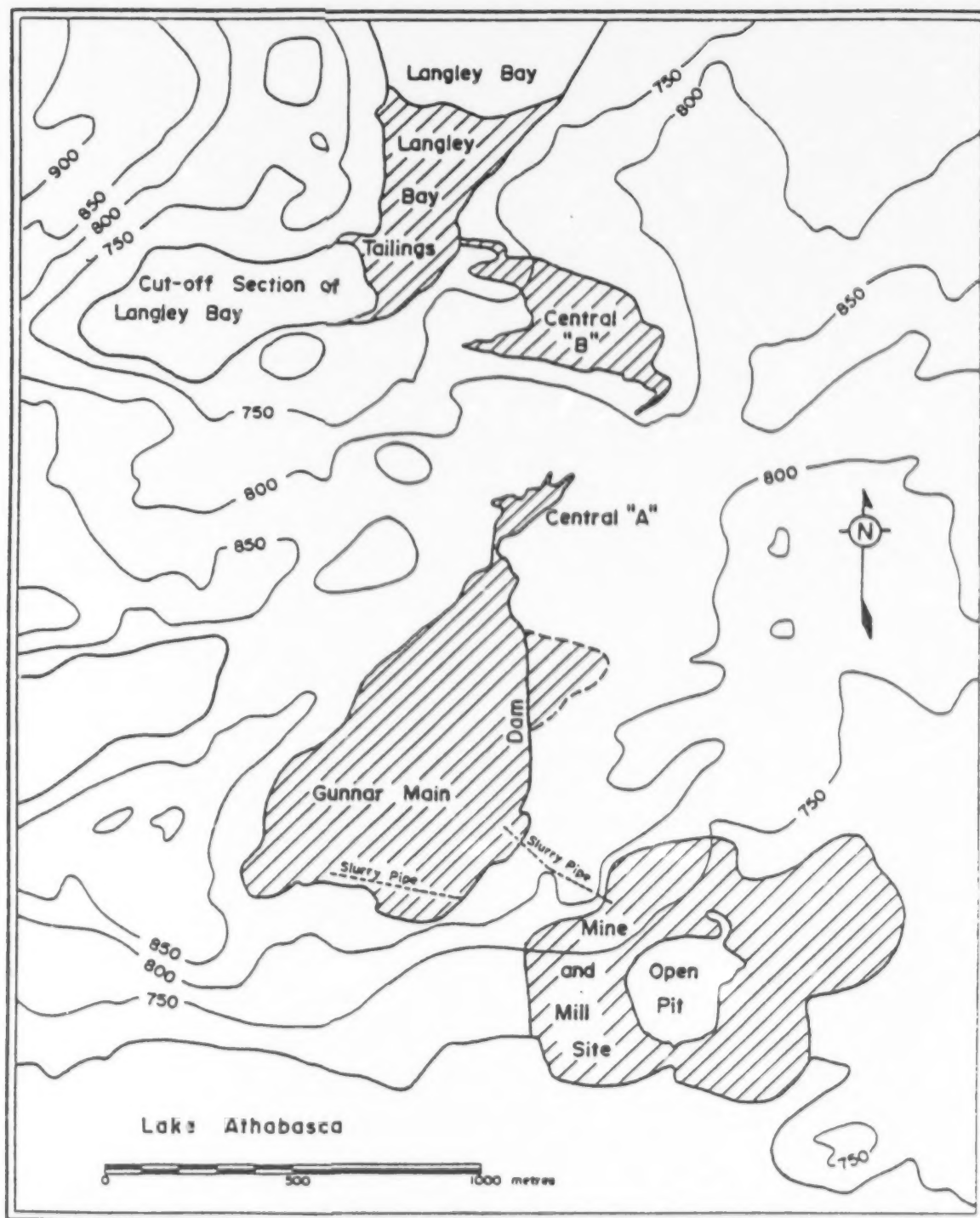


Figure D-21. Gunnar tailings site (D-6)



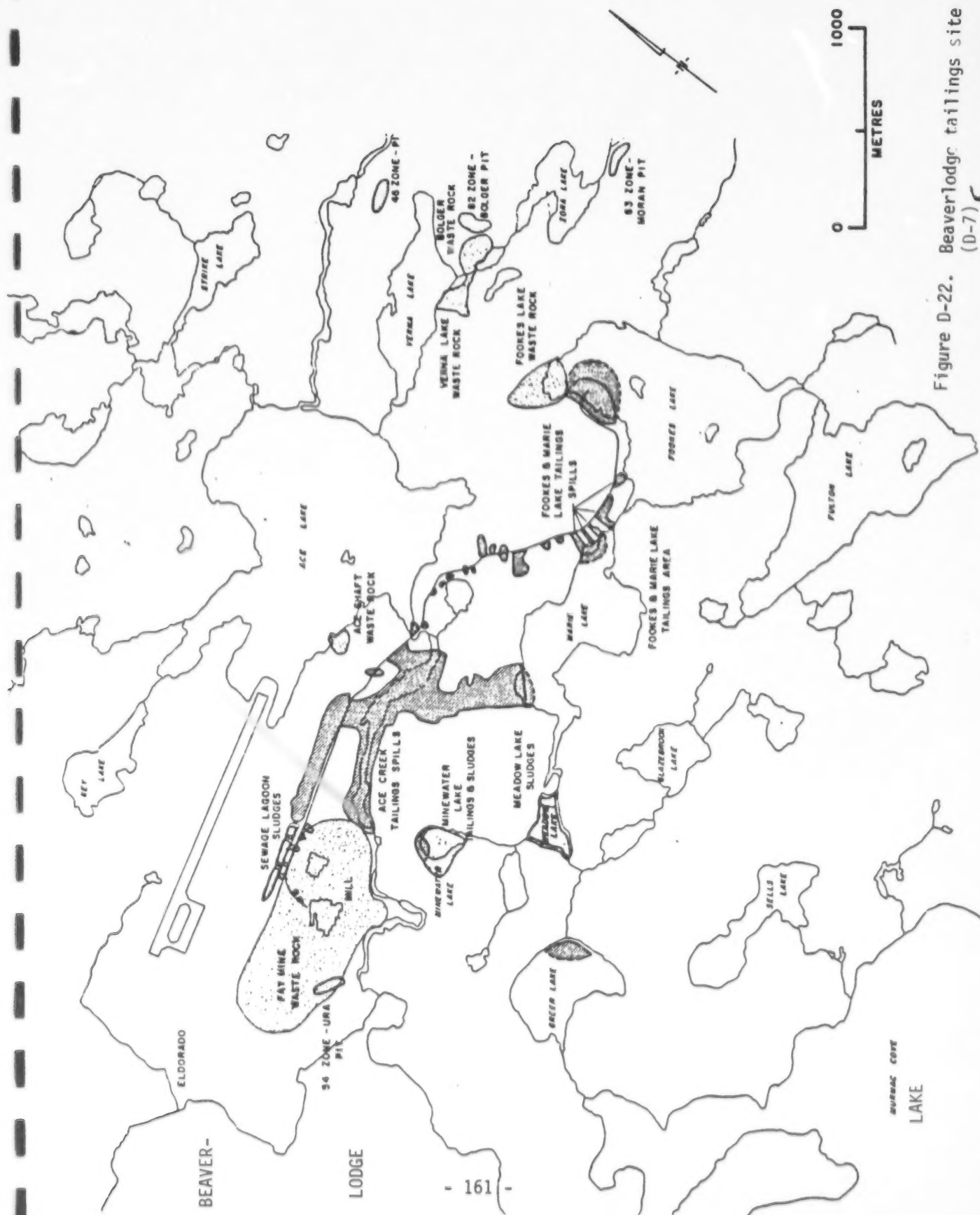
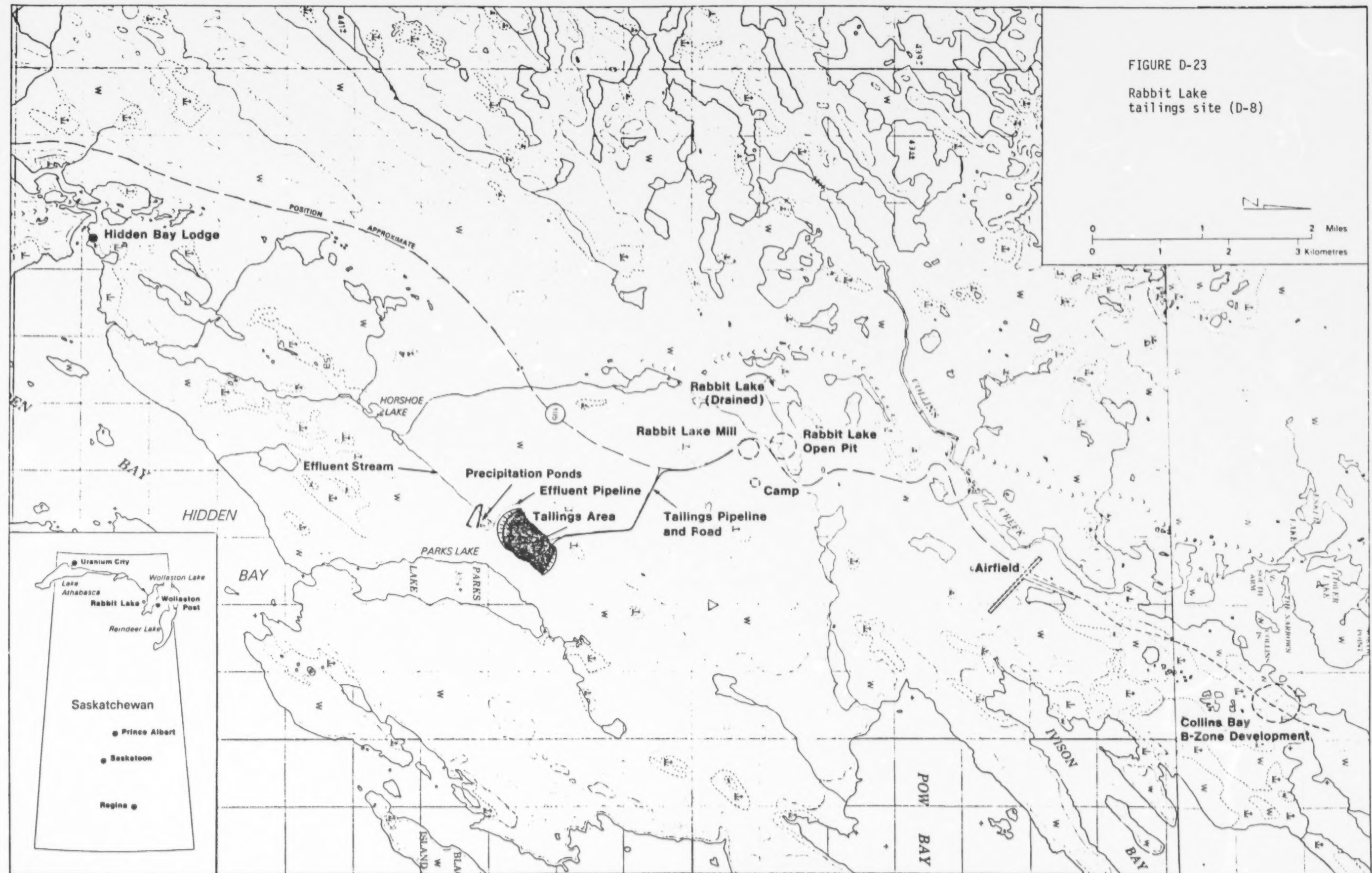


Figure D-22. Beaverlodge tailings site (D-7)

FIGURE D-23

Rabbit Lake  
tailings site (D-8)



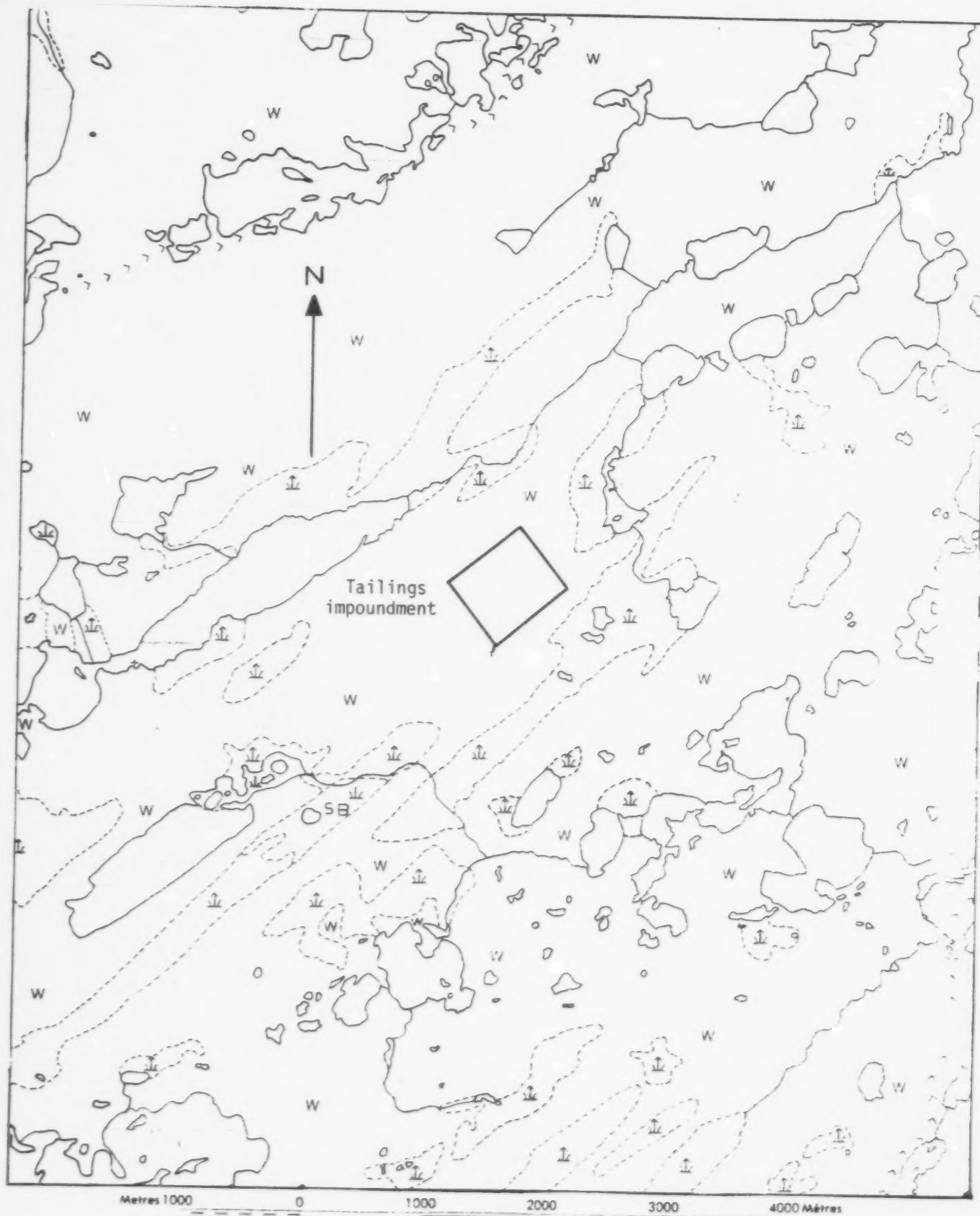


Figure D-24. Key Lake tailings site (D-9)

## REFERENCES

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- (D-2) Kalin, M. (1983). "Long-term ecological behaviour of abandoned uranium mill tailings - 1. Synoptic survey and identification of invading biota". Institute of Environmental Studies, University of Toronto.
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- (D-6) Swanson, S. and Abouguendia, Z. (1981). "The problem of abandoned uranium tailings in northern Saskatchewan - an overview". Saskatchewan Research Council Report No. C-805-48-C-81, Saskatchewan Research Council, Saskatoon, Saskatchewan.
- (D-7) Eldorado Nuclear Limited (1982). Decommissioning of the Beaverlodge Mine/Mill Operations and Reclamation of the Site.
- (D-8) MacLaren Engineers and Geocon (1984). Feasibility Study of Decommissioning Alternatives for the Rabbit Lake Tailings Area. Report to Eldor Mines.
- (D-9) Topographic map "Zimmer Lake, Saskatchewan". Series A701, Map 74 H/4, Edition 1 MCE, Surveys and Mapping Branch, Energy, Mines and Resources Canada, Ottawa, Ontario.